The Status and Reach of the NOvA Experiment

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NuMI Off-Axis ν_e Appearance (NOvA) Experiment

36 Institutions from 7 countries; 181 collaborators

Argonne National Laboratory·University of Athens·Banaras Hindu University·California Institute of Technology·Institute of Physics of the Academy of Sciences of the Czech Republic·Charles University, Prague·University of Cincinnati·Czech Technical University·University of Delhi·Fermilab·Federal Univ. of Goias· IndianInstitute of Technology, Guwahati·Harvard University·Indian Institute of Technology·University of Hyderabad·Indiana University· Iowa State University·University of Jammu·Lebedev Physical Institute·Michigan State University·University of Minnesota, Crookston·University of Minnesota, Duluth·University of Minnesota, Twin Cities·Institute for Nuclear Research, Moscow·Panjab University·University of South Carolina·Southern Methodist University·Stanford University·University of Sussex·University of Tennessee·University of Texas at Austin·Tufts University·University of Virginia·Wichita State University·Winona State University·College of William and Mary

Outline

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  - Physics goals
  - Experimental setup
- The NOvA Detectors
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- NOvA Operational Status
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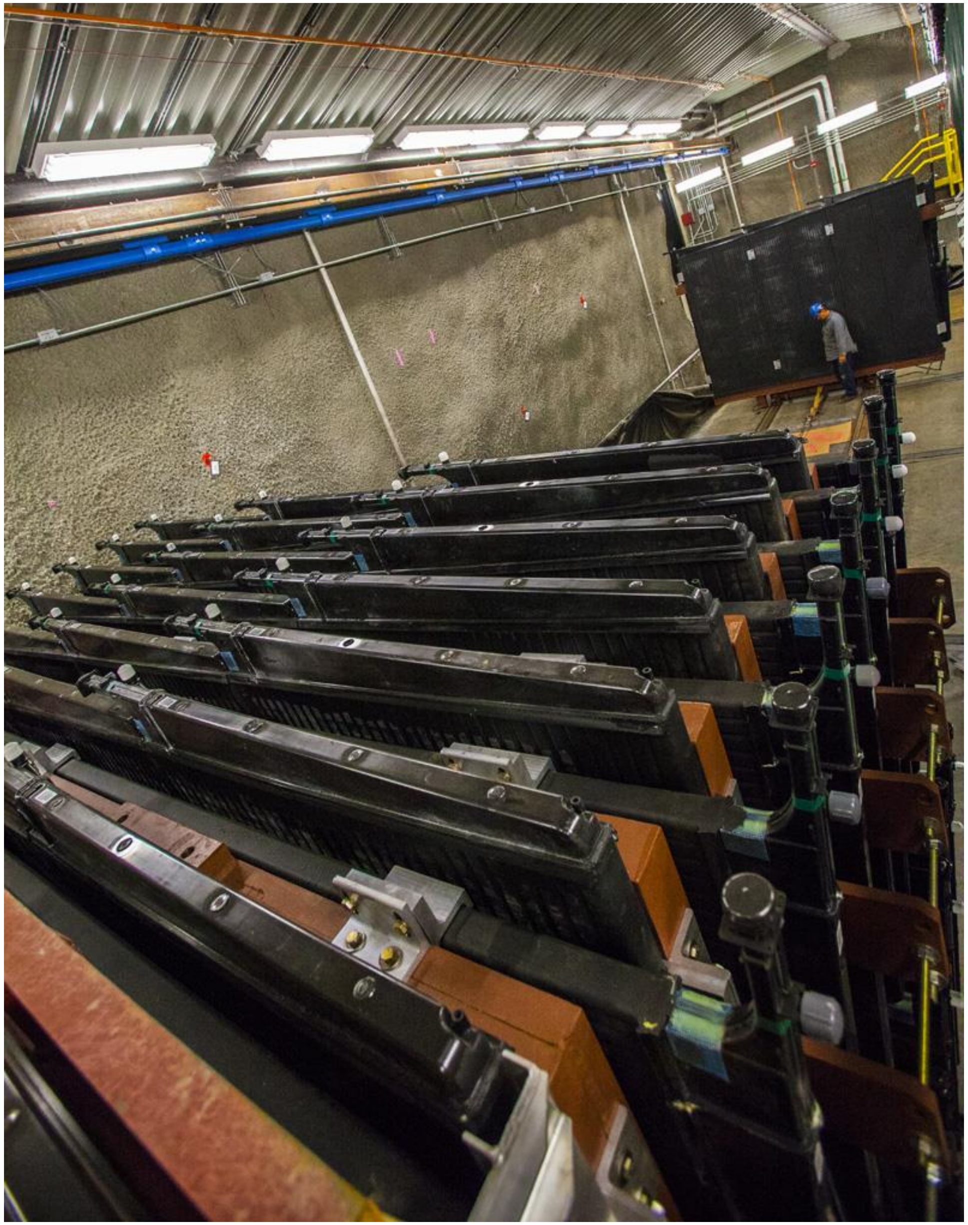
  - Construction status
- $\nu_\mu \rightarrow \nu_e$ Appearance
  - Distinguishing electron neutrino events
  - Data driven background corrections
  - Physics reach
- $\nu_\mu \rightarrow \nu_\mu$ Disappearance
  - Distinguishing muon neutrino events
  - Physics reach



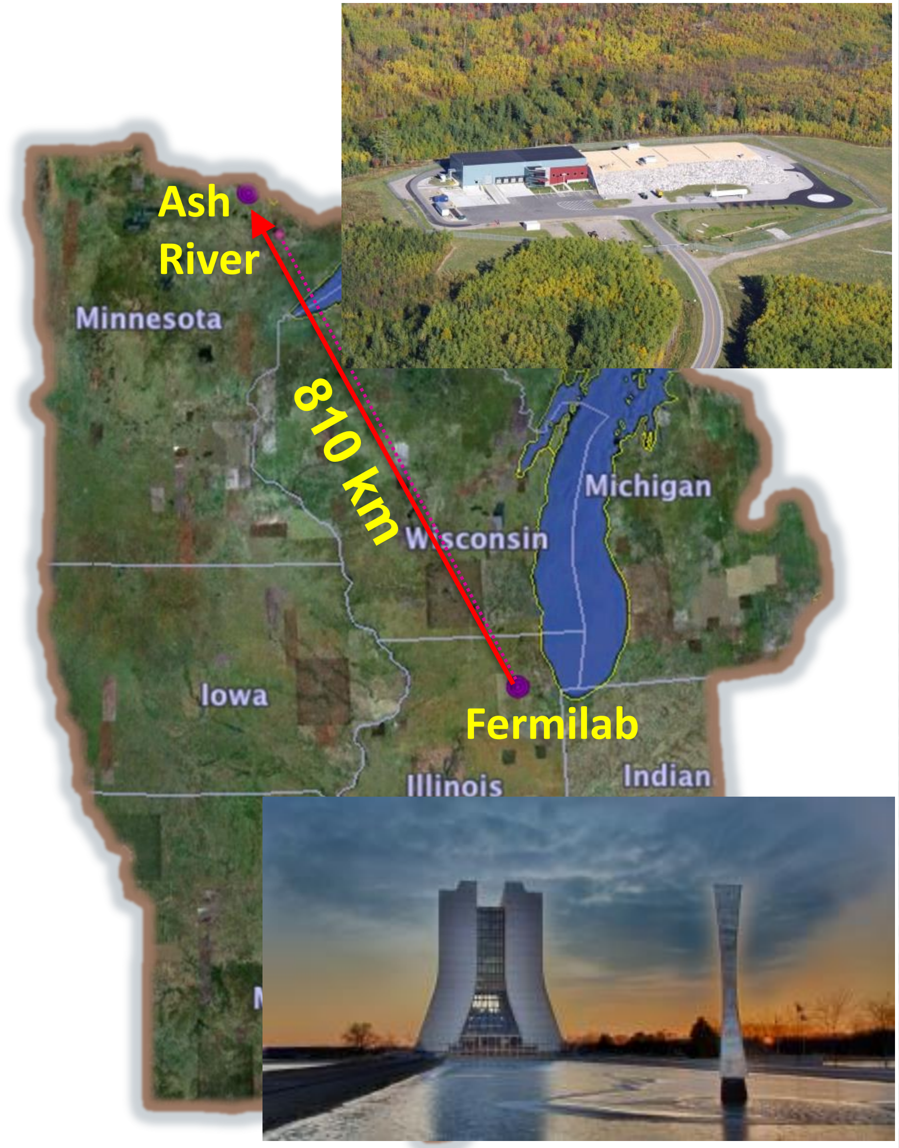
The NOvA Experiment

NOvA Physics Goals

- Observe $\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  - Measure θ_{13} via ν_e appearance
  - Determine the neutrino mass hierarchy
  - Search for neutrino CP violation
  - Determine the θ_{23} octant
- Observe $\nu_\mu \rightarrow \nu_\mu$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$
  - Precision measurements of $|\Delta m^2_{32}|$, θ_{23}
  - Over-constrain the atmospheric sector
- Broad non-oscillation physics programme
  - Neutrino cross-sections at the Near Detector
  - Sterile neutrinos
  - Supernova neutrinos and monopoles
  - Non-Standard neutrino Interactions (NSI)

NOvA Experiment Setup Overview

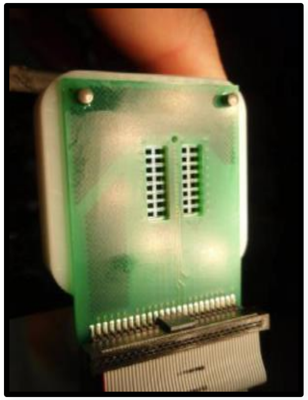
- Upgraded NuMI muon neutrino beam at Fermilab from 300 to 700 kW
- 810 km baseline from Fermilab to Ash River, Minnesota
  - Long underground path to Far Detector leads to ~30% matter effects
- Two functionally identical detectors, optimised for ν_e identification
  - 14 kt liquid scintillator Far Detector on the surface at Ash River (3m earth-equivalent of barite)
  - A ~300 ton Near Detector (~100m underground) at Fermilab, 1 km from source
- Detectors placed 14 mrad off the NuMI beam axis



The NOvA Detectors

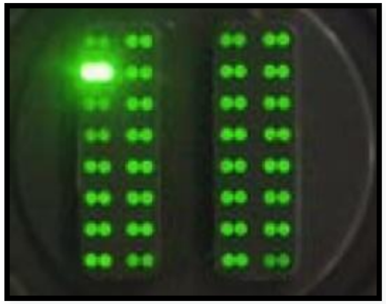
The NOvA Detectors

- 14-kton Far Detector (~3x MINOS)
  - 63% active detector
  - 344,064 detector cells read by avalanche photodiodes (APDs)
- 0.3 kton Near Detector
  - 18,000 cells/channels.
- Each plane just 0.15 X_0 Great for e^- vs π^0 separation

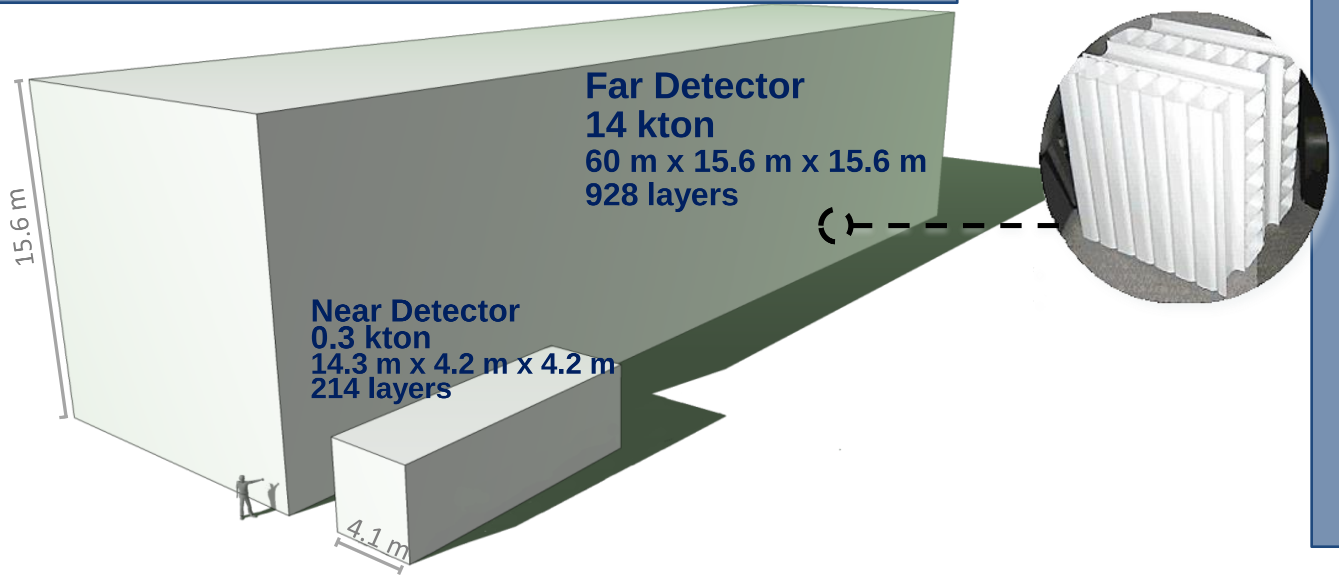


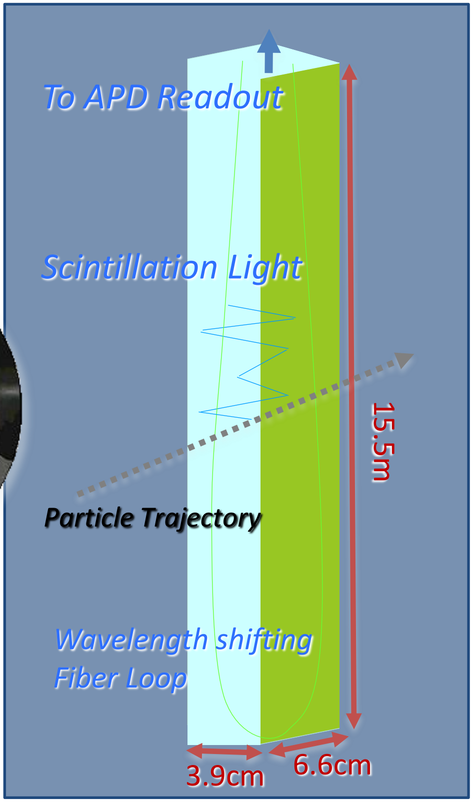
32-pixel APD

Fiber pairs from 32 cells



Extruded plastic (PVC) cells filled with 9 ktons of scintillator instrumented with λ-shifting fiber and APDs



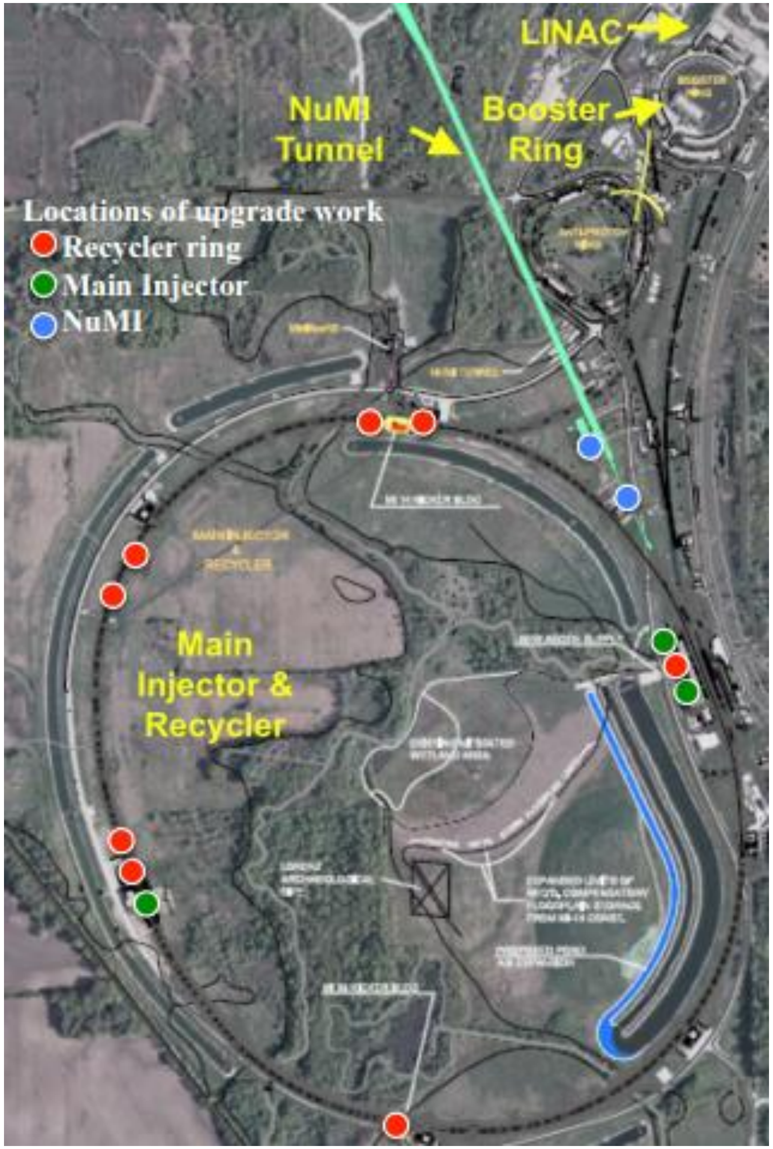


The NOvA Detectors

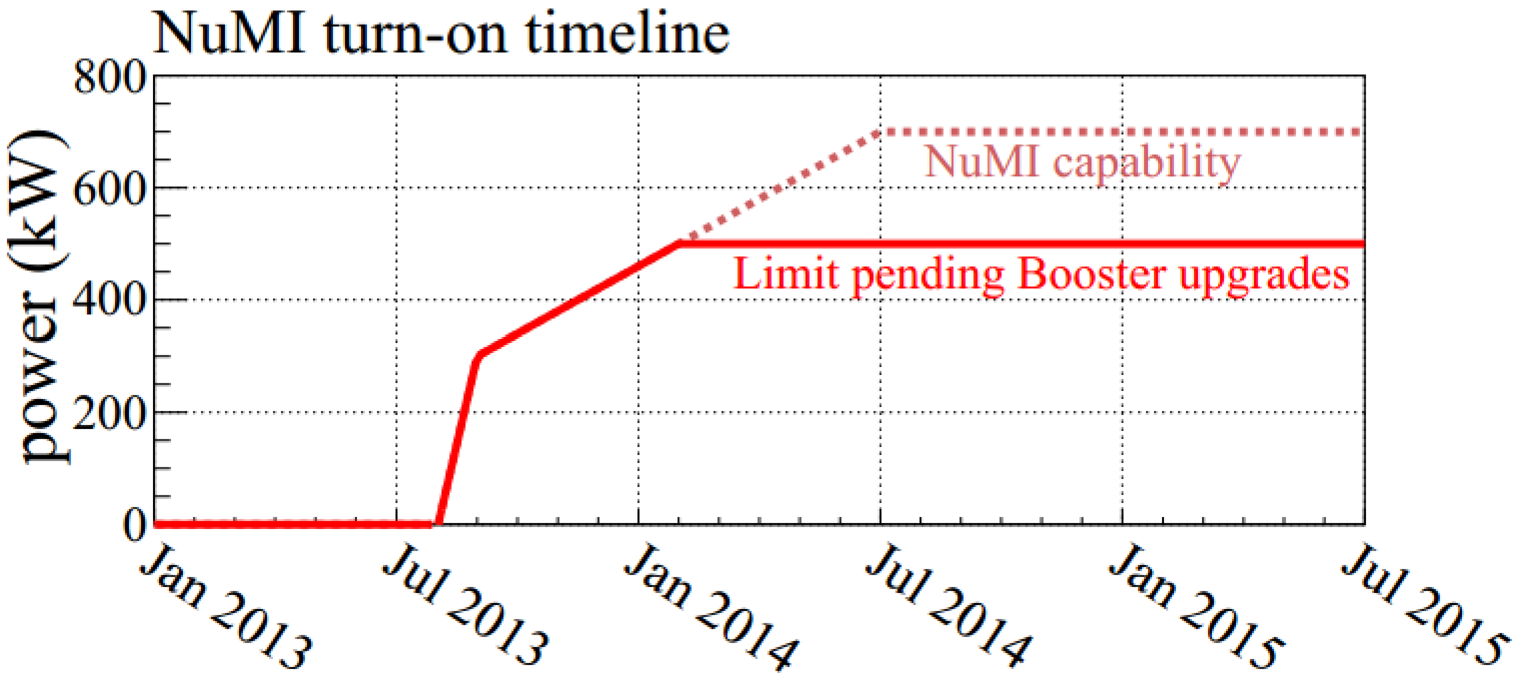
NOvA Operational Status

Accelerator and NuMI upgrades

- Fermilab has completed a series of upgrades to the Main Injector and Recycler rings to reduce the cycle time from 2.2 s to 1.3 s
  - 10 μs beam spill every 1.3 s
- Intensity increased from 300 to 700 kW
- Neutrino beamline optimised for NOvA

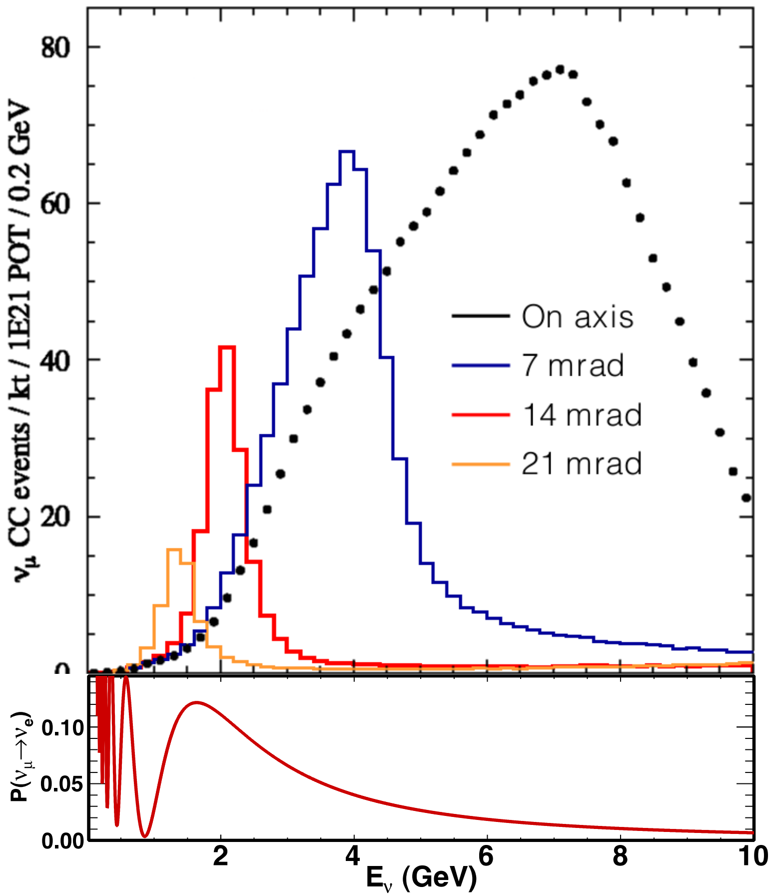


Return of the NuMI beam



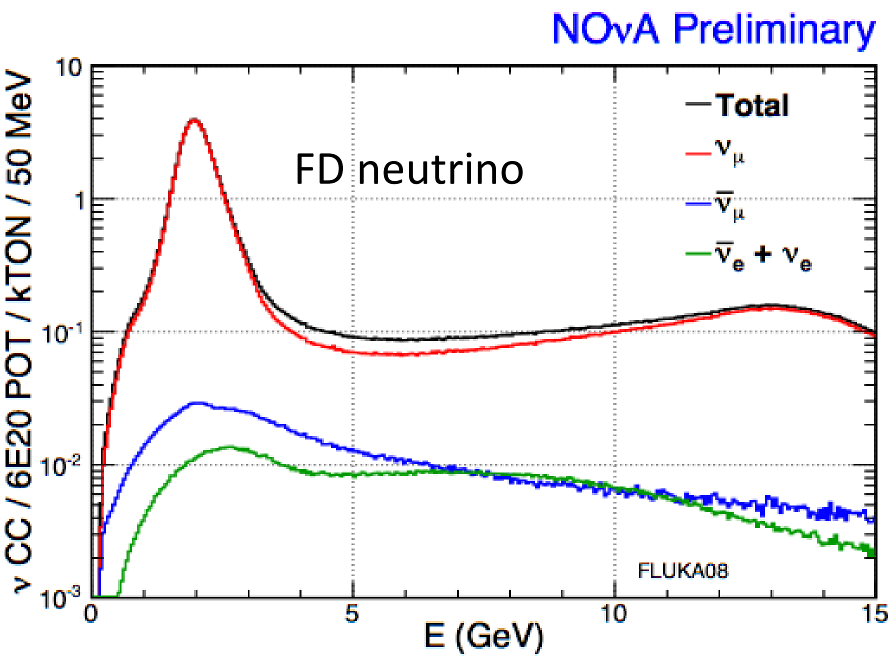
- Commissioning of the NuMI beam has begun and will continue through end of the year
  - Beam to target hall achieved August 5th
  - Horn and target scans with beam should happen any day now
- Routine operation of the neutrino beam is expected in September
- 300 kW (pre-shutdown capability) → 500 kW achieved by use of recycler and reduction of cycle time in Main Injector
- Limited in short-term to ~500 kW until Booster RF system upgrades are complete

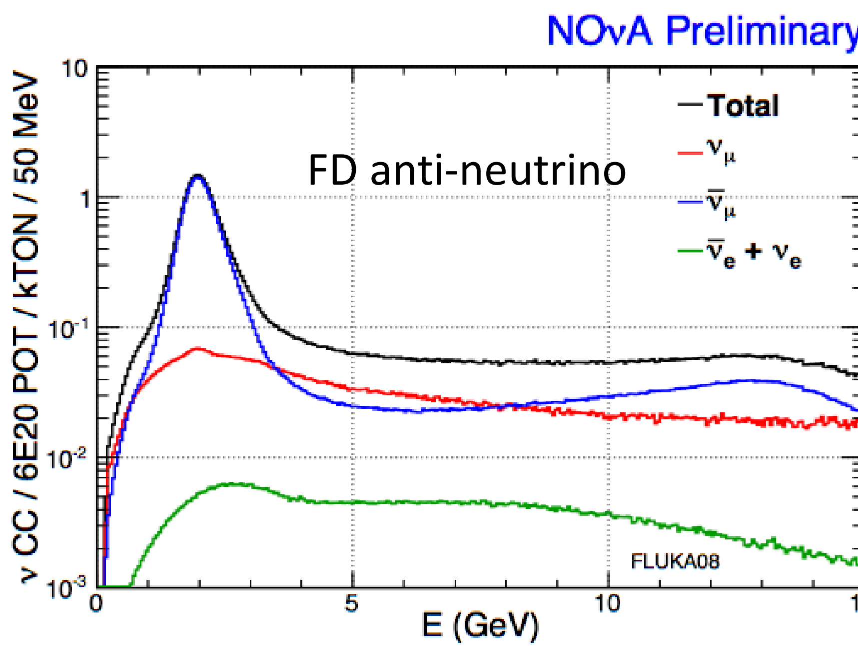
The off-axis NuMI beam



- The choice of a 14 mrad off-axis position from the NuMI beam for the NOvA detector, allows for a narrow band beam which in conjunction with topology of final state particles, allows one to more easily reject potential backgrounds
- The peak of the beam coincides with the oscillation maximum for electron neutrino appearance for the 810 km distance

The NuMI Beam spectra: ν_μ and $\bar{\nu}_\mu$





- The NOvA off-axis beam has a peak in the 1-3 GeV signal region with 1.6% wrong sign contamination and 0.6% beam ν_e
- For anti-neutrino configuration has only 10% wrong sign contamination and 0.8% beam ν_e

Far Detector Construction Progress

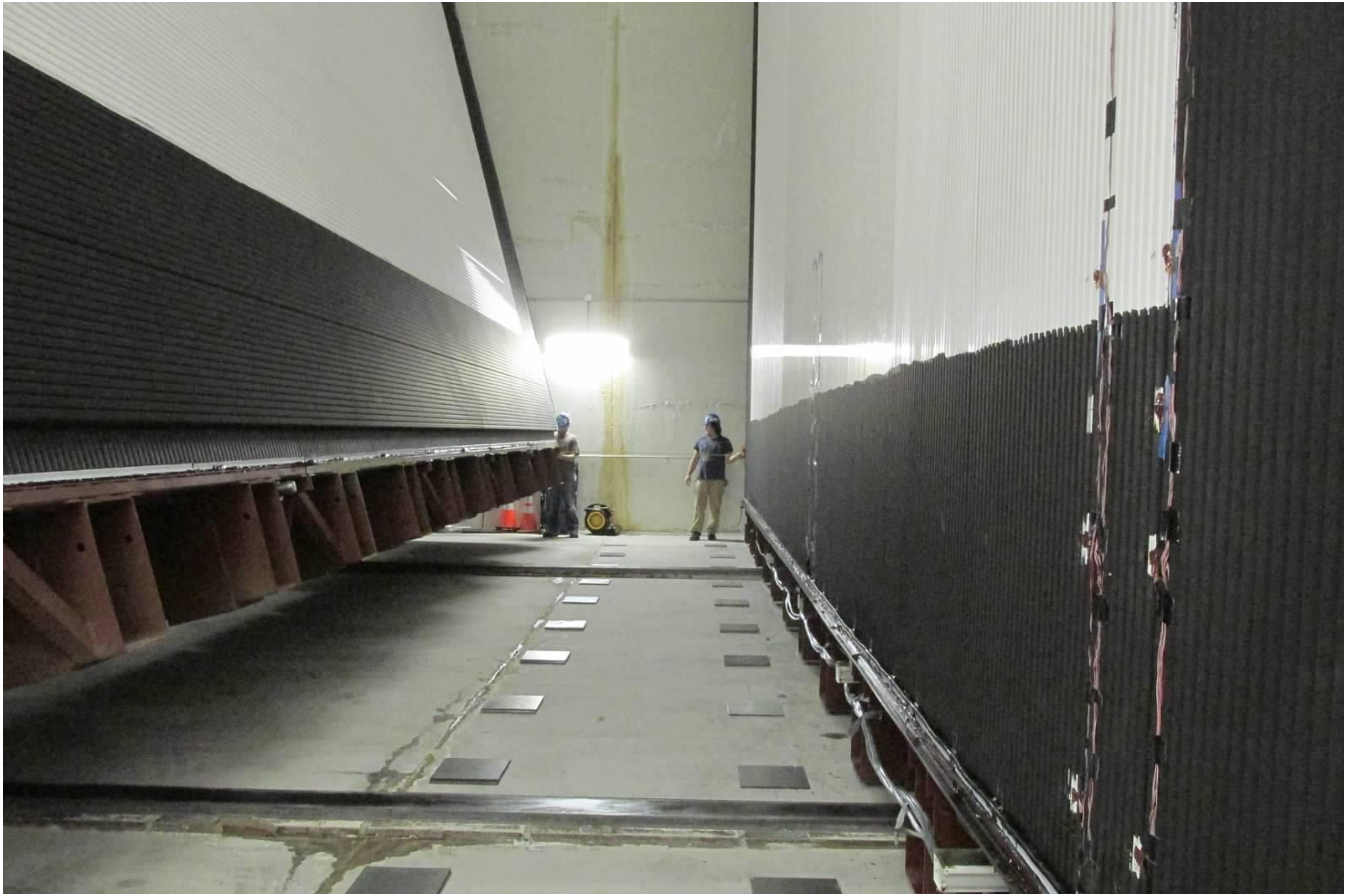
Far Detector Construction Progress

Far Detector status in August 2012

Far Detector Construction Progress

Far Detector Construction Progress

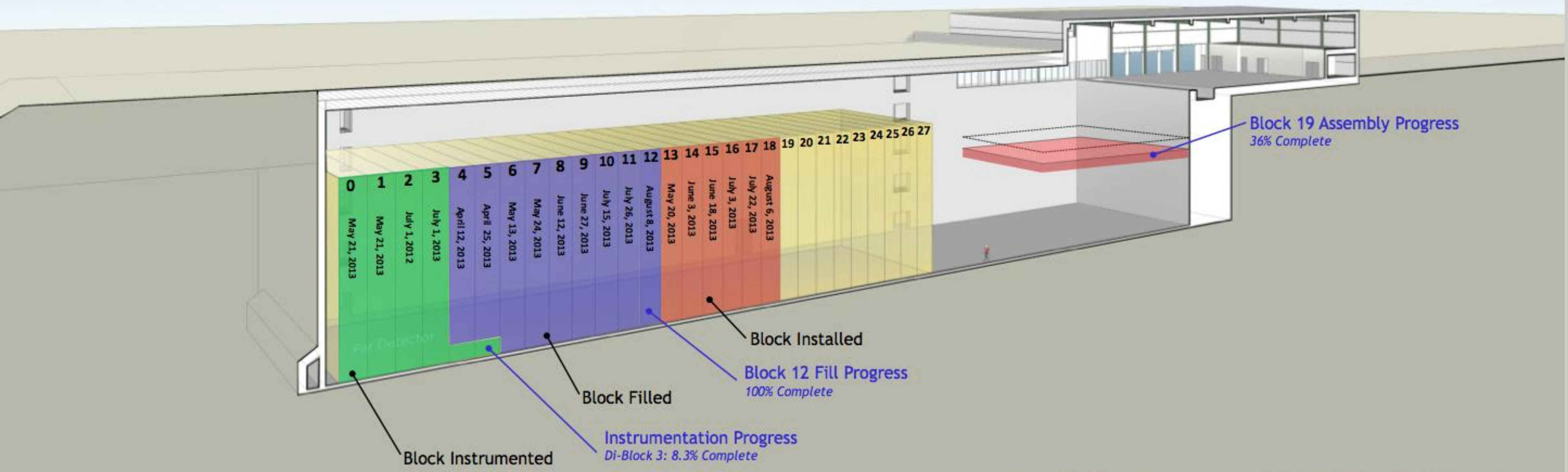
Far Detector Construction Progress



Far Detector Construction Progress

Far Detector status in August 2013

Status as of August 26th 2013



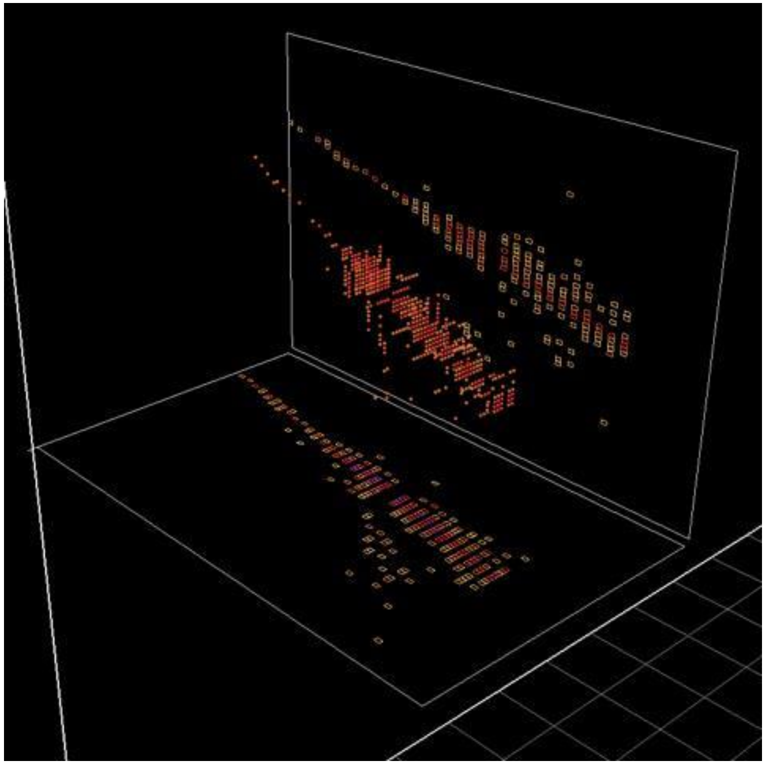
14 kilotons = 28 NOvA Blocks

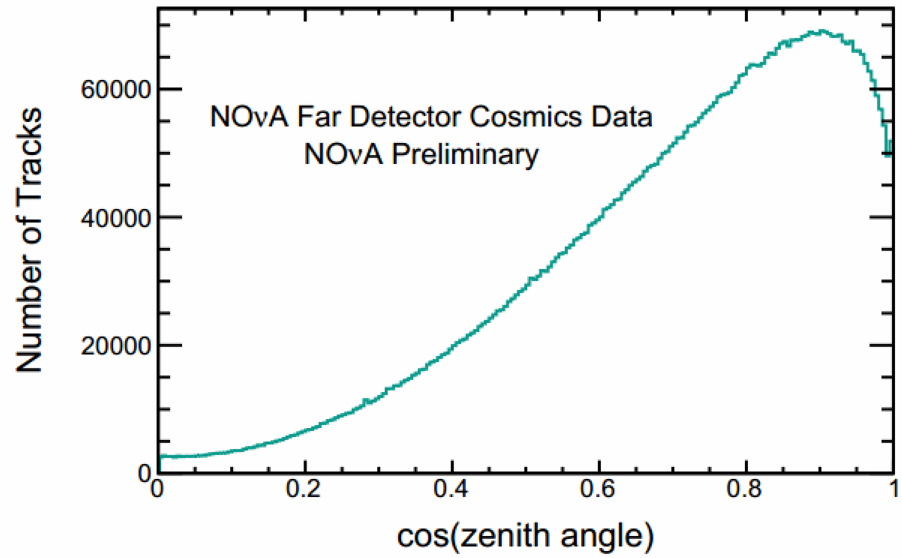
19 blocks of PVC modules are assembled and installed in place

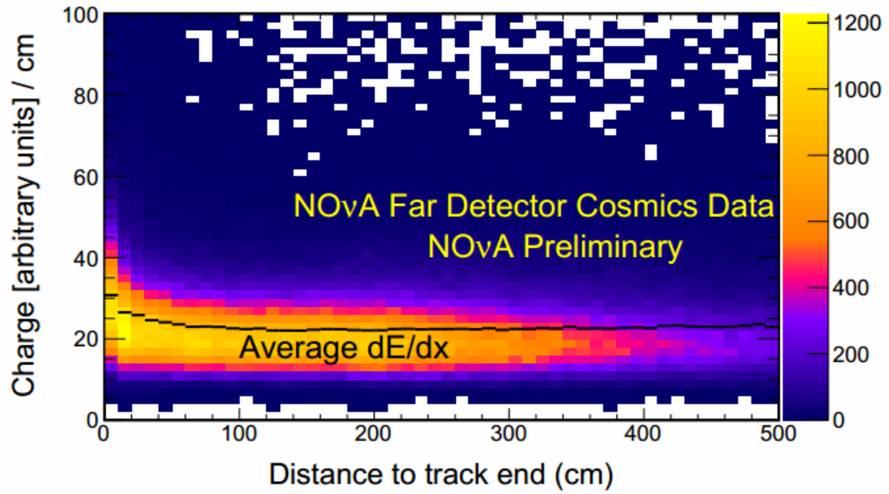
13.0 blocks are filled with liquid scintillator

4.17 blocks are outfitted with electronics

Far Detector First Cosmic Ray Data



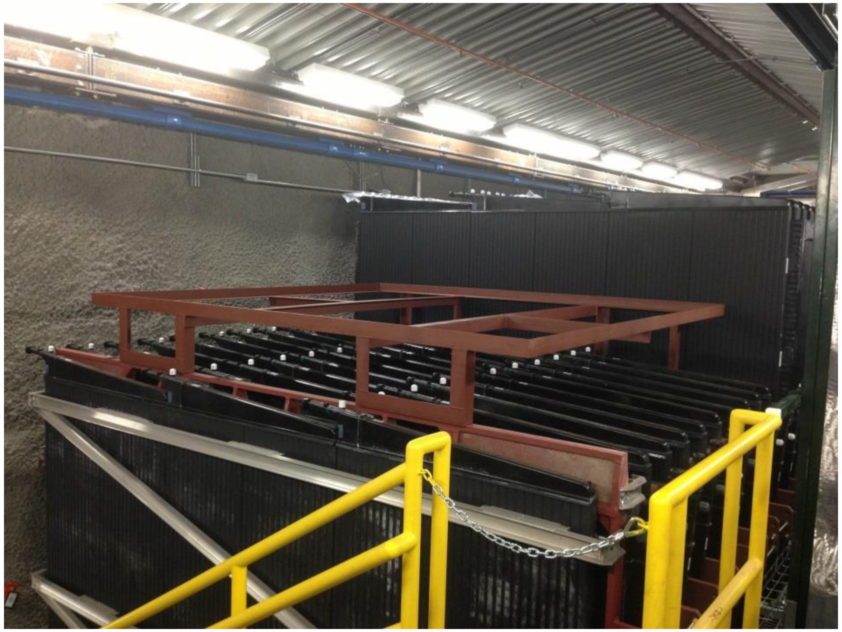




- ❑ First kton of the Far Detector was instrumented May 21st 2013
  - Now have two kton instrumented
- ❑ Reconstruction algorithms already tested on cosmic ray data collected
- ❑ Captured many examples of above 3D display of a cosmic ray event

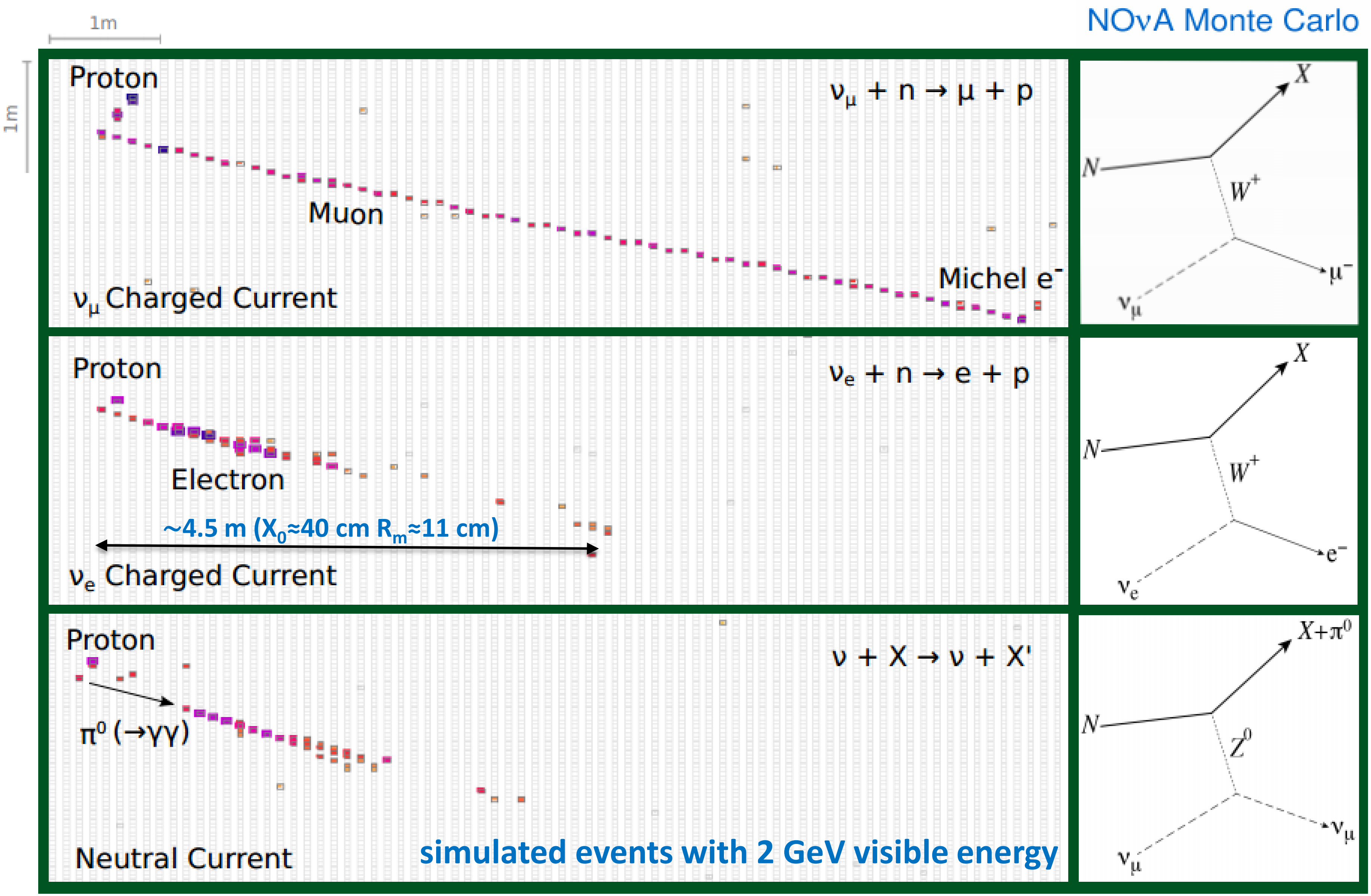
Near Detector Construction Progress

- Near Detector Muon Catcher installed August 1st 2013
- First block installed August 21st 2013
- First half of Near Detector (downstream half) to be installed by the end of this year
- Second (upstream) half to installed by summer of 2014



$\nu_\mu \rightarrow \nu_e$ Appearance

NOvA Neutrino Event Topologies



Electron-neutrino Appearance in NOvA

- NOvA measures the probability of ν_e appearance in a ν_μ beam

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$

$$\overset{(+)}{\underset{-}{}} \; 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

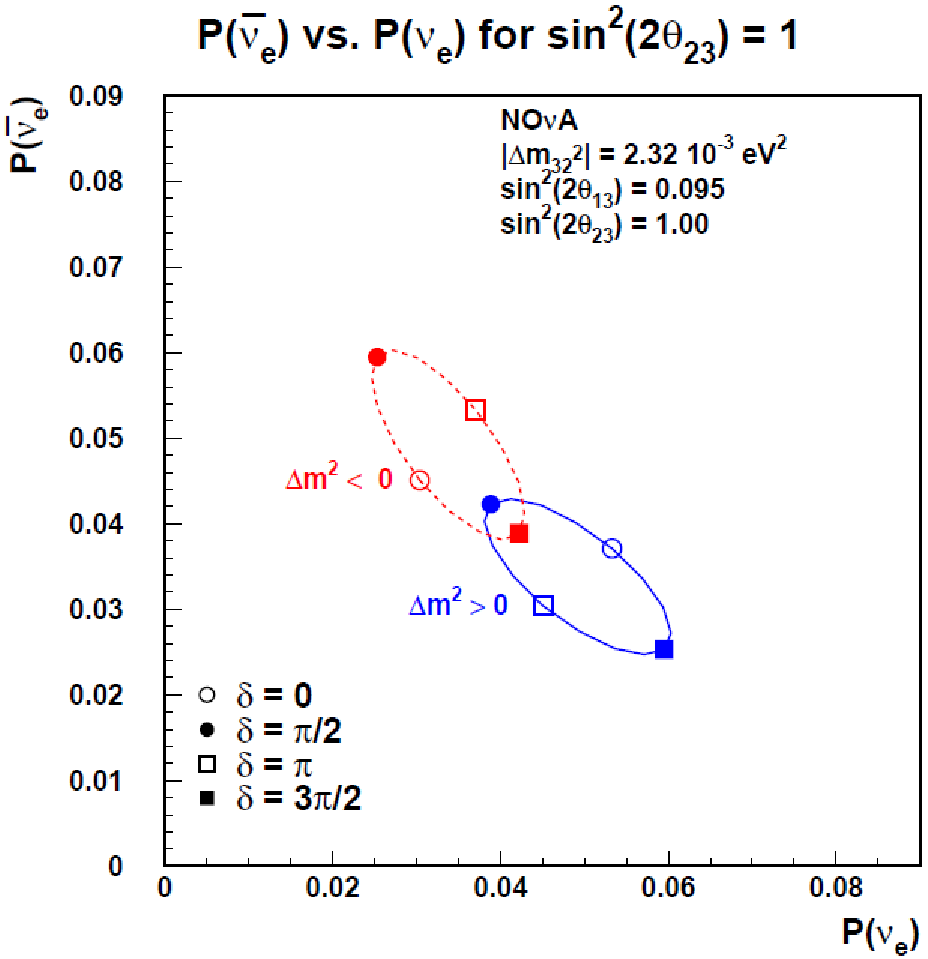
$$+ \; 2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$

$$\alpha = \Delta m^2_{21}/\Delta m^2_{31} \qquad \Delta = \Delta m^2_{31} L/(4E) \qquad A = \overset{(-)}{\underset{+}{}} G_f n_e L/(\sqrt{2}\Delta)$$

- $\sin^2(2\theta_{13})$ can be accessed in long baseline searching for ν_e events
- $\sin^2(2\theta_{13})$ has been measured which allows us to make measurements of δ_{CP}
- Note that we can gain information about the $\boldsymbol{\theta_{23}}$ octant since $\sin^2(\theta_{23})$ is a coefficient on the leading-order term above
- Probability is enhanced or suppressed due to matter effects which depend on the mass hierarchy, i.e the sign of $\Delta m^2_{31} \sim \Delta m^2_{32}$ as well as neutrino vs. anti-neutrino running

Electron-neutrino Appearance in NOvA

- NOvA will measure: $P(\nu_\mu \rightarrow \nu_e)$ at 2 GeV and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ at 2 GeV



- Large θ_{13} is good news for NOvA. It reduces the overlap between these bi-probability ellipses, reducing the likelihood of degeneracies.

Electron-neutrino Appearance in NOvA

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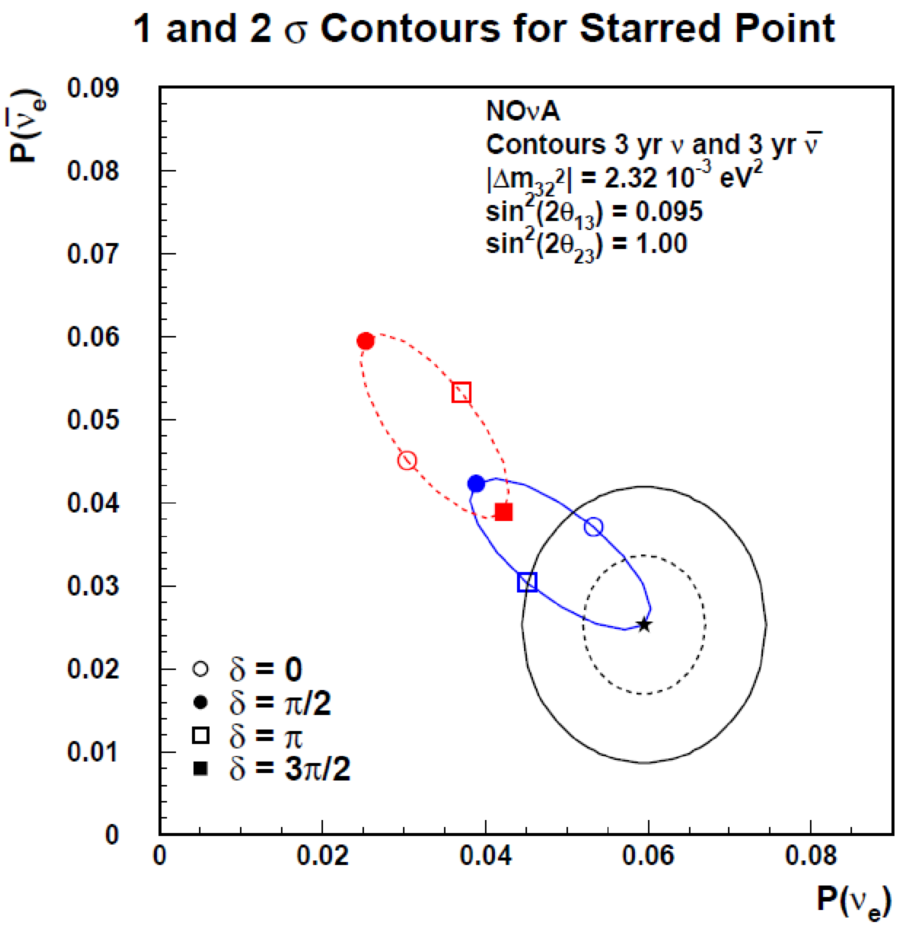
- Example NOvA result



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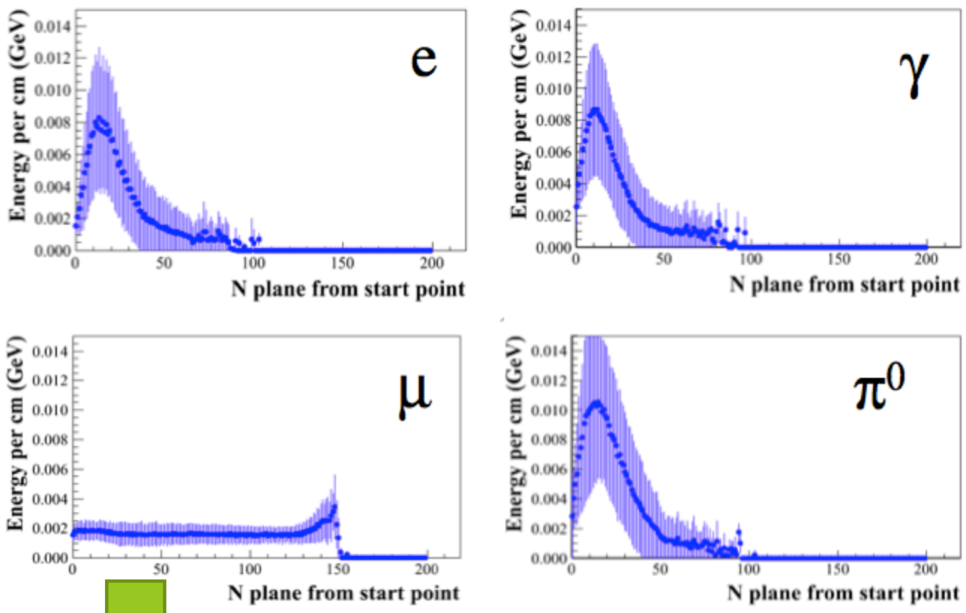
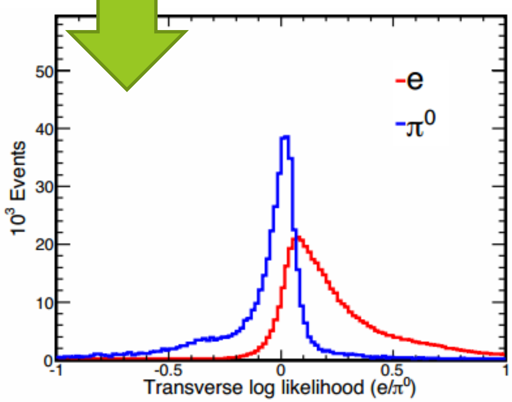
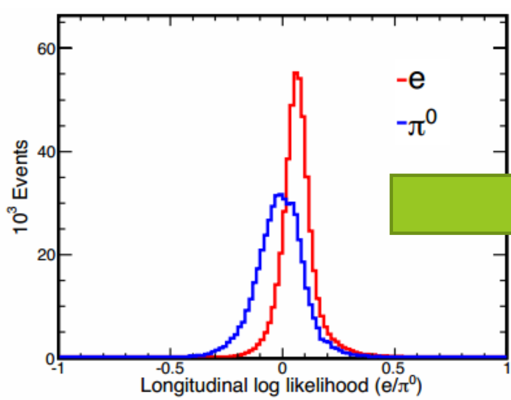
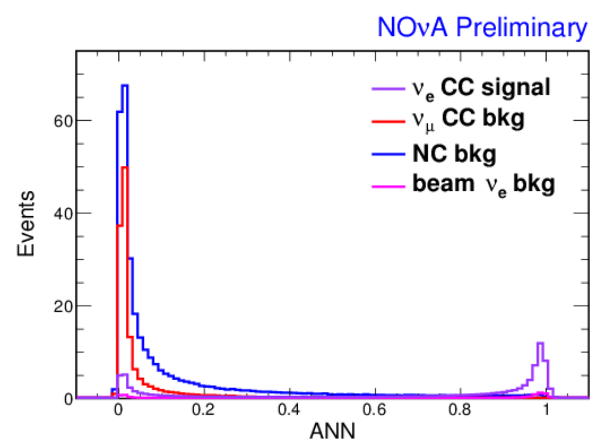
Selecting electron neutrino events



- The fine-grained nature of the NOvA detectors allows us to distinguish the details of energy profiles for different particles
- We parameterise particle energy profiles using the transverse and longitudinal dE/dx, and then create likelihoods for each particle hypothesis
- We combine shower shape information with an artificial neural network







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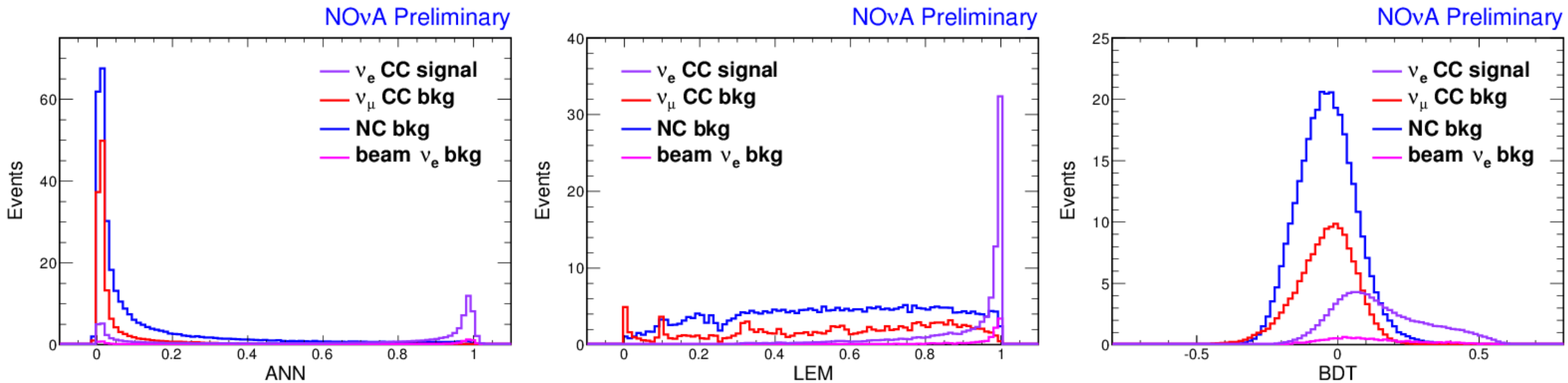


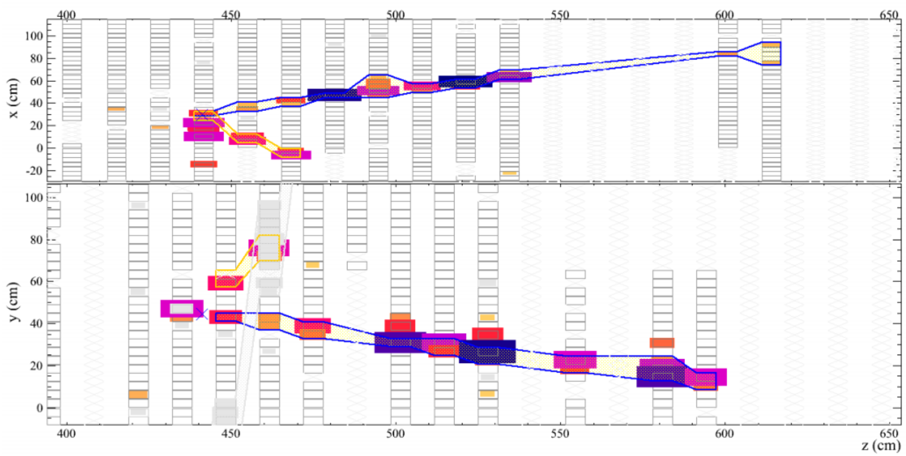
- Several event identification algorithms have been developed to separate the ve signal from various backgrounds:
  - ANN: artificial neural network using shower shape-based likelihood for particle hypotheses.
  - LEM: library event matching, match to library of MC events (based on MINOS technique)
  - BDT: boosted decision tree on simple reconstructed quantities
- Typical $S/(S+B)^{1/2} \simeq 6.5$

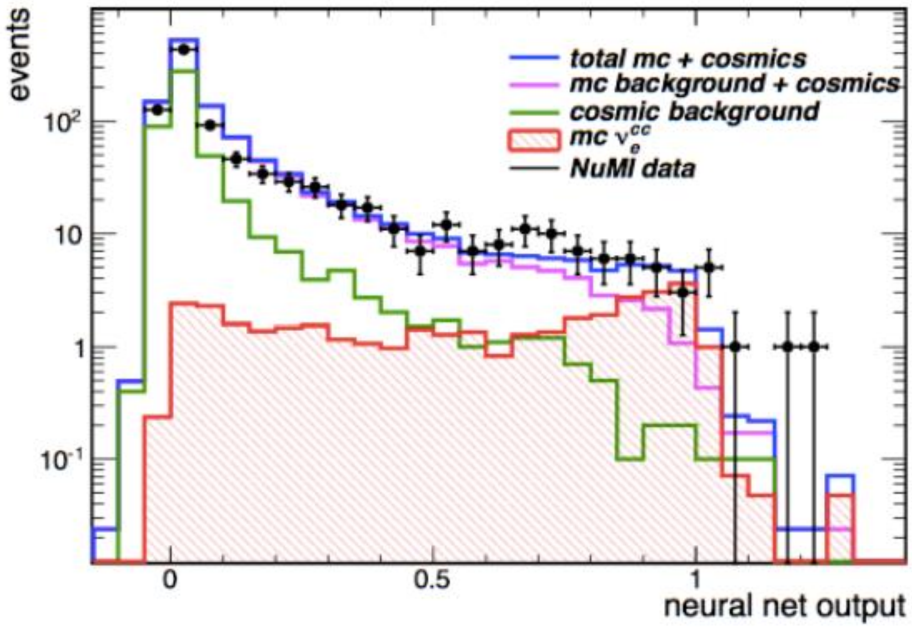
ANN	signal	total bkgd	NC bkgd	ν_μ CC bkgd	ν_e CC bkgd
ν (3 yrs)	56	28	17	4	7
$\bar{\nu}$ (3 yrs)	26	14	9	1	4

ν_e identification in the NOvA prototype

- We successfully ran the reconstruction and particle ID chain on the NuMI data recorded at the NOvA prototype Near Detector On the Surface (NDOS)

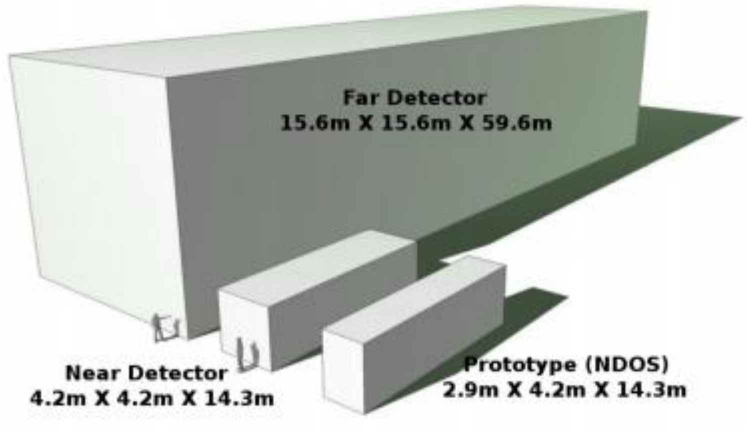
- We observe evidence of the electron neutrino component of the beam



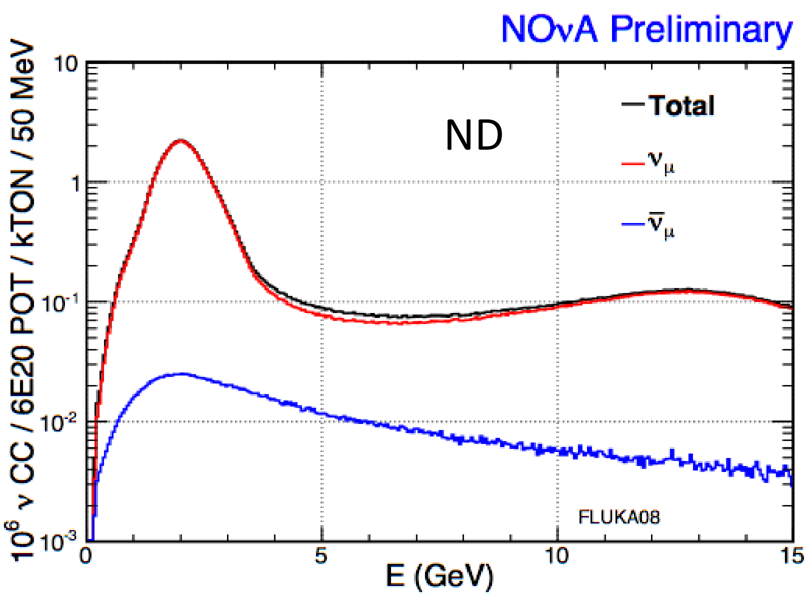


Background Estimations using Near Detector

- Near Detector provides a high-statistics data sample to estimate the background
  - Disagreements within uncertainties of the model
  - Expected due to modeling of hadronic shower

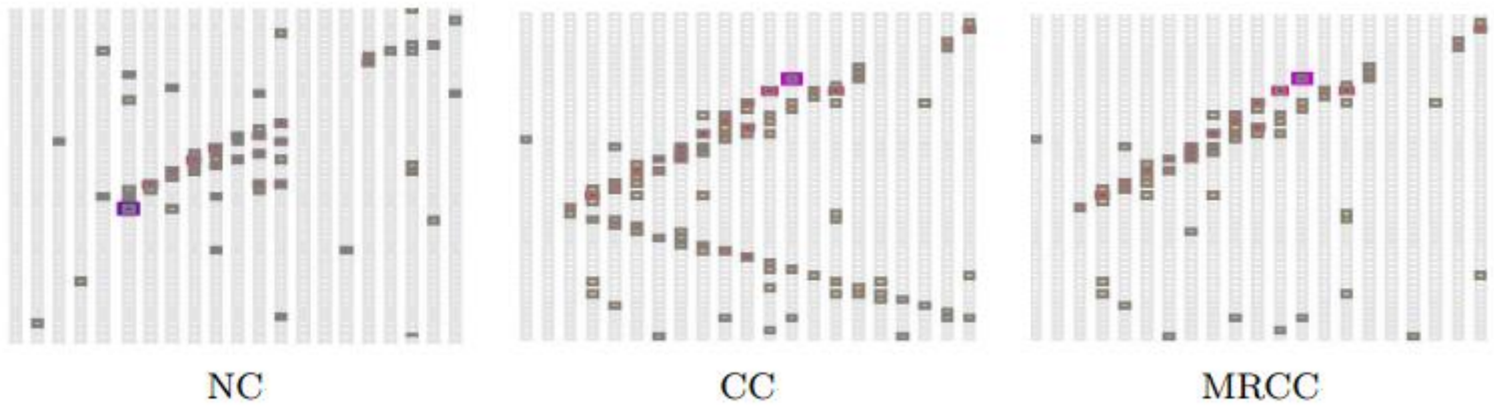


- We have developed data-driven methods to measure the different background components
  - MRCC method



Background Estimations using Near Detector

- Remove the muon track in a selected ν_μCC event and use the rest as a hadronic shower-only event
- Muon Remove Charged Current (MRCC) events give us a well understood sample of hadronic showers
- ν_μCC events without the muon look a lot like Neutral Current events, which are the main background to the ν_e analysis
- Well defined ν_μCC spectra, with well known efficiency and purity from the ν_μ disappearance analysis



Simulated events

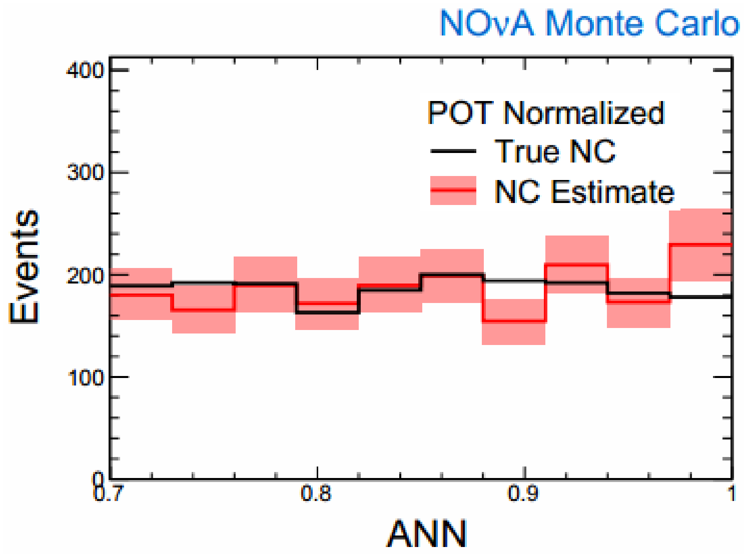
Using MRCC as a data-driven correction

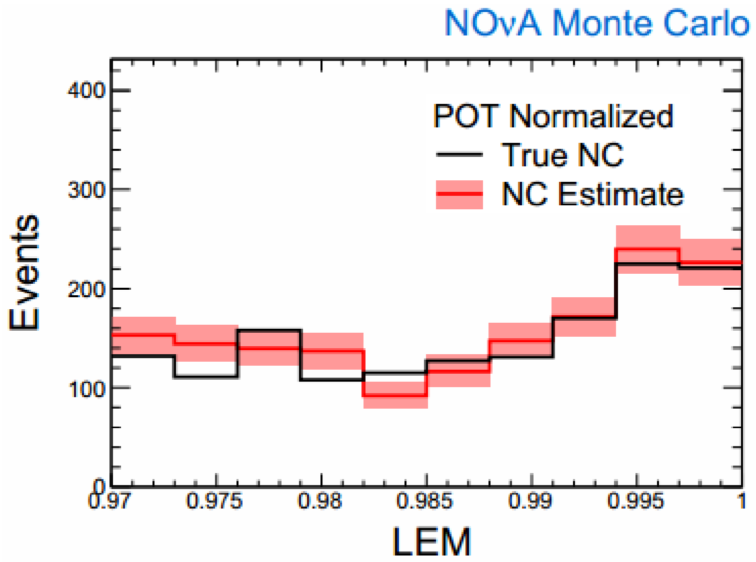
- We use the data/MC ratio from MRCC to obtain a data-driven correction that is applied to the standard NC events as a function of energy

$$NC^{BG} = \frac{NC^{MC}}{MRCC^{MC}} \times MRCC^{Data}$$

- Many systematic effects cancel in the ratio, resulting in a more accurate estimate of background

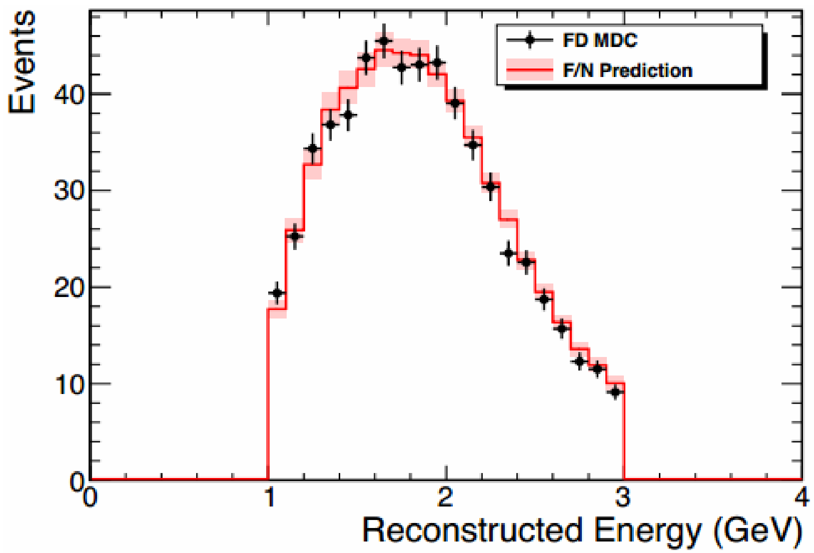
- Estimate of Neutral Current background in pseudo-data on the right yields results consistent with MC truth





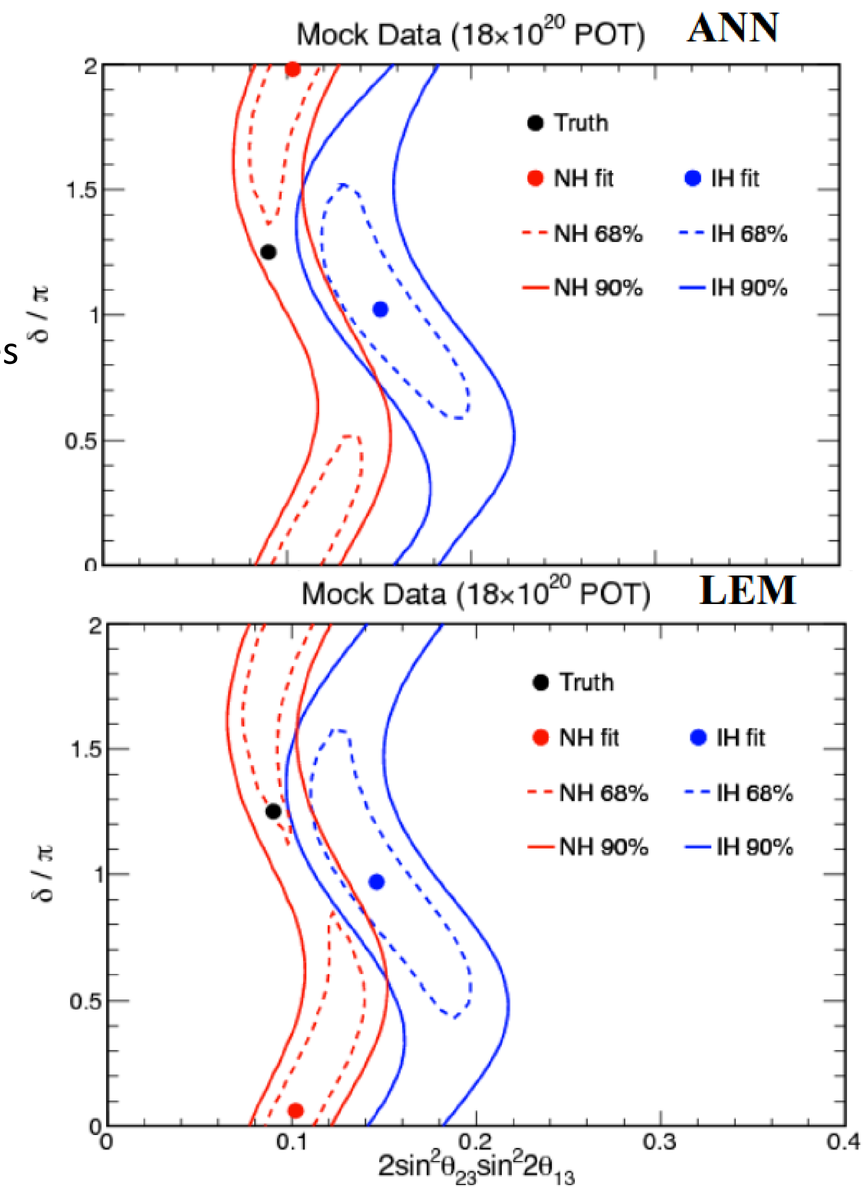
Predicting the Far Detector background

- The Near Detector ν_e-selected NC and ν_μ CC background components are corrected by the Far/Near MC ratio
- Far/Near ratio accounts for geometry, fiducial volume ratio, intensity, detector differences and oscillations



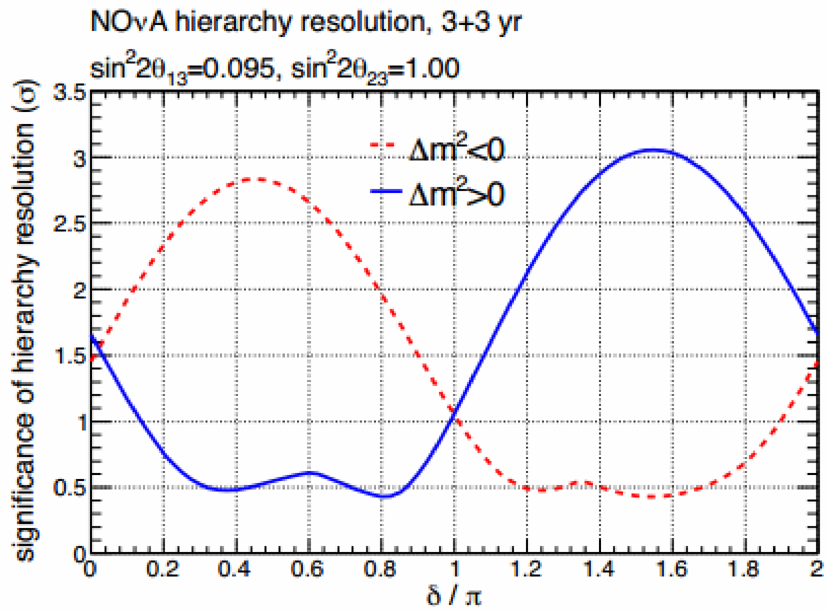
NOvA sensitivities in δ_{CP} vs. $\sin^2 2\theta_{13}$

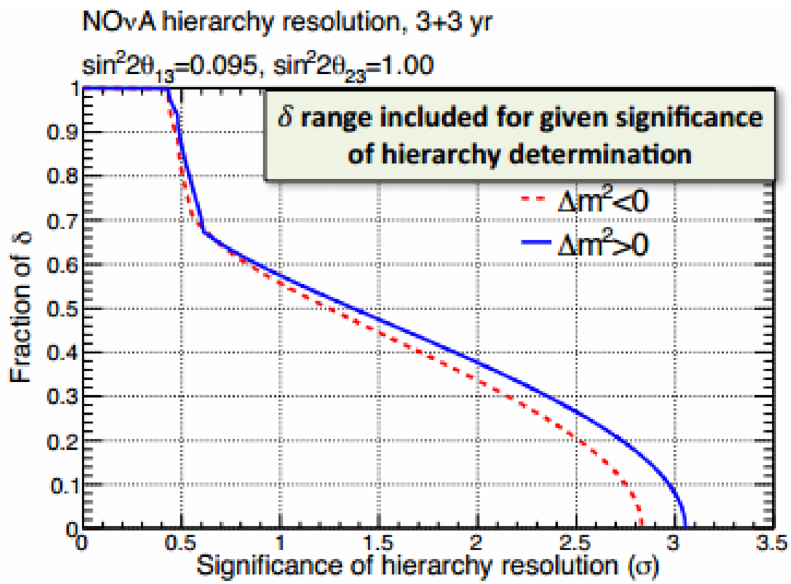
- Plot shows 90% CL limits in δ_{CP} vs. $\sin^2 2\theta_{13}$
  - Shown at the NOvA best fit value for $|\Delta m^2_{32}|$ and $\sin^2 2\theta_{23}$.
  - For both normal and inverted mass hierarchies
- A Feldman-Cousins method was used
- Results are for primary selection and primary separation method
- *Results are consistent with secondary selection and cross-check method; agree with truth within ~1σ*



Resolution of the mass hierarchy

- Now that θ_{13} has been measured we can individually look at our resolution for resolving the mass hierarchy
- Significance of mass hierarchy resolution using energy spectrum
- Energy fit provides improvement on the fully degenerate δ_{CP} values





- Results from full simulation, reconstruction, selection and analysis framework
  - FD only. Extrapolation methods from ND in progress

Resolution of the mass hierarchy

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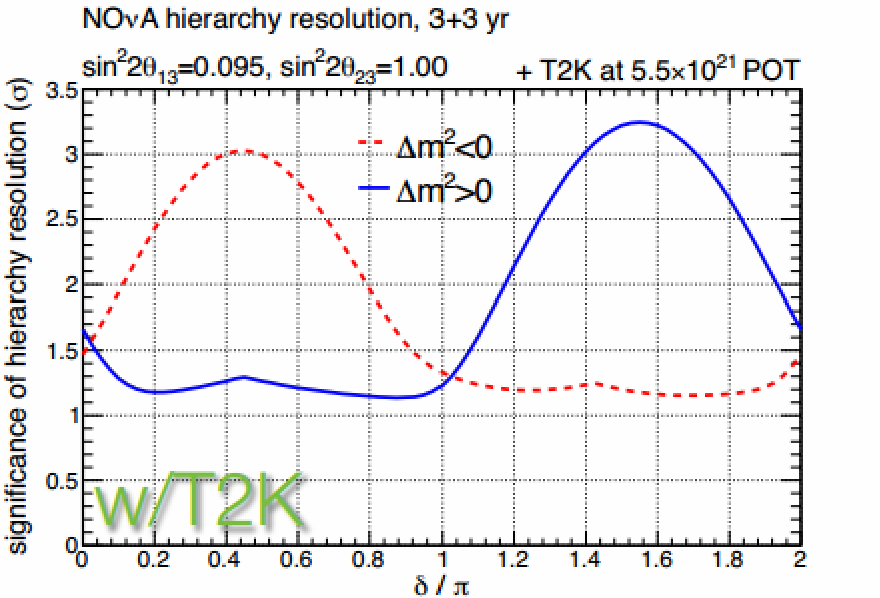
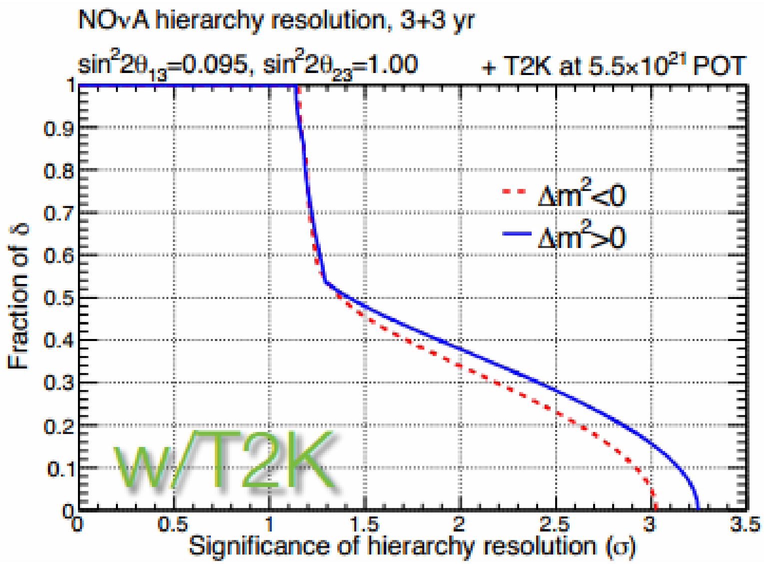
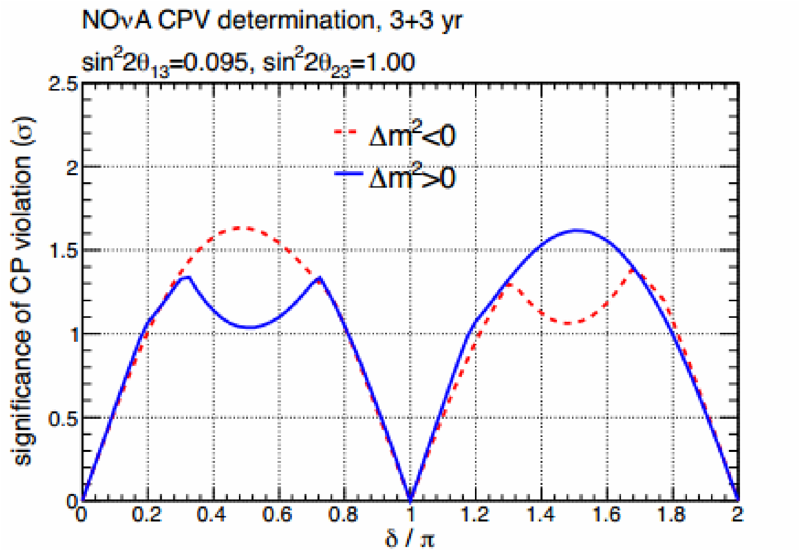


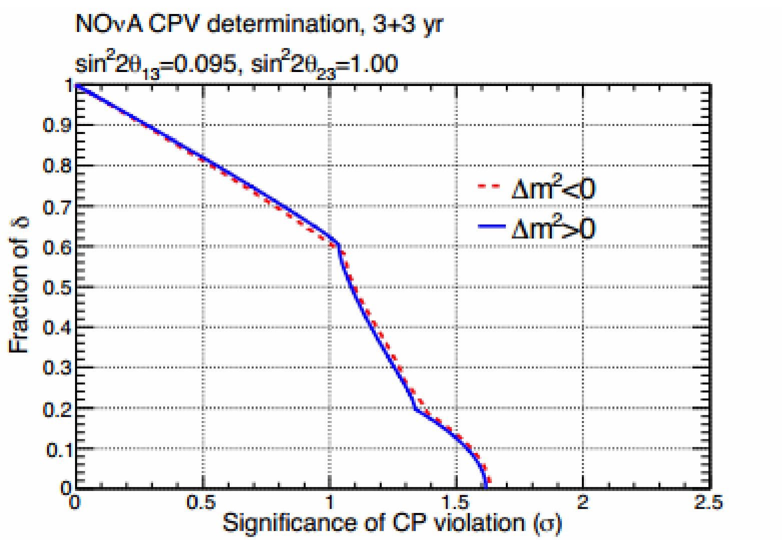


- Differences in baseline/matter effects between NOvA and T2K can provide additional information

Study of CP violation phase

- Significance of CP violation using energy spectrum
- Assumes that mass hierarchy is unknown





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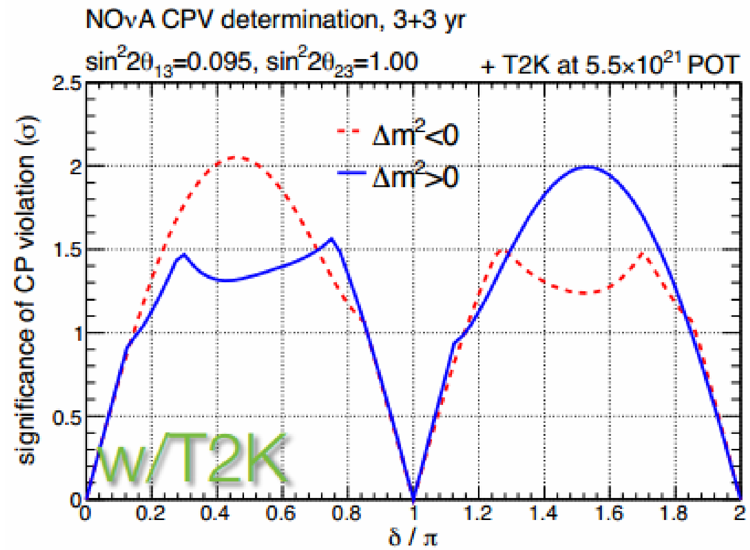

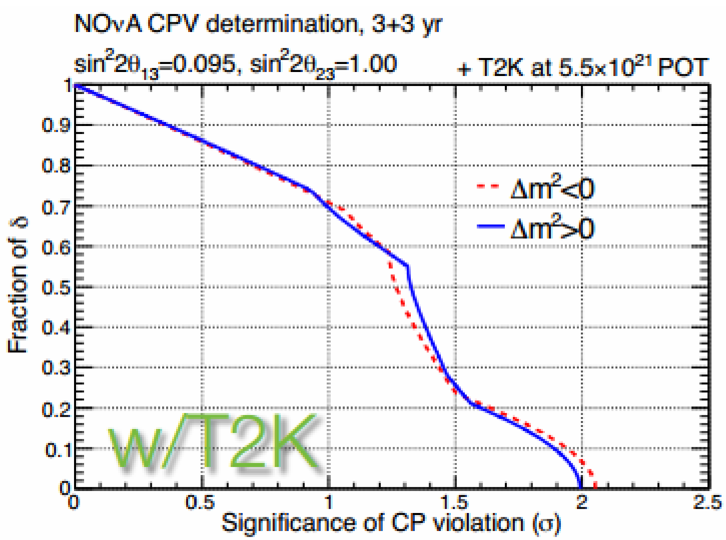

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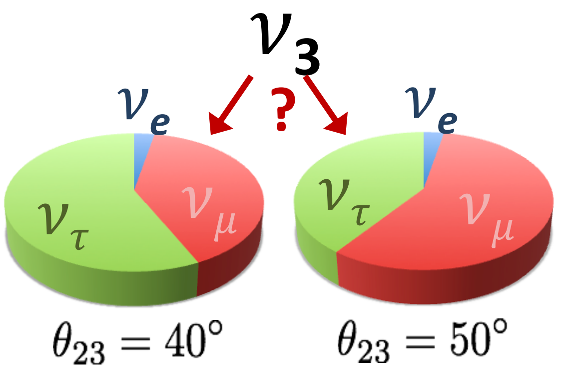
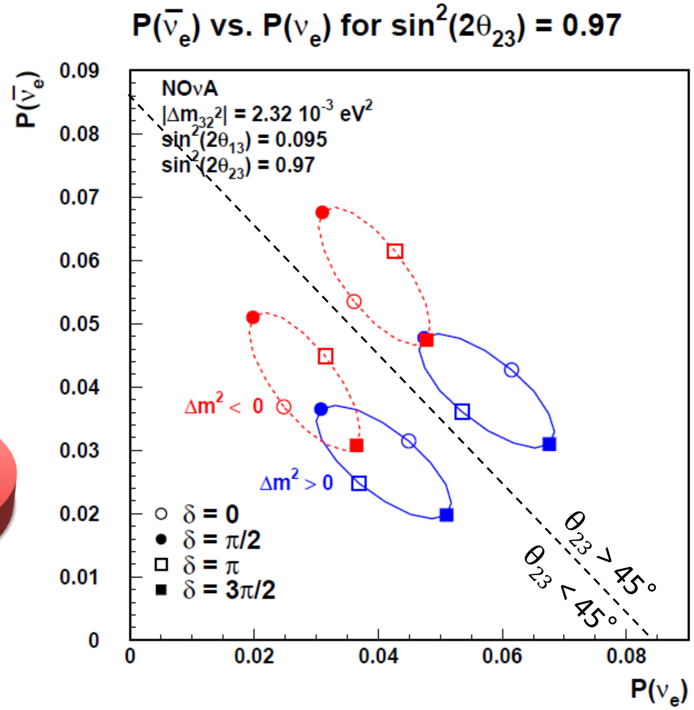
Non-maximal $\sin^2 2\theta_{23}$





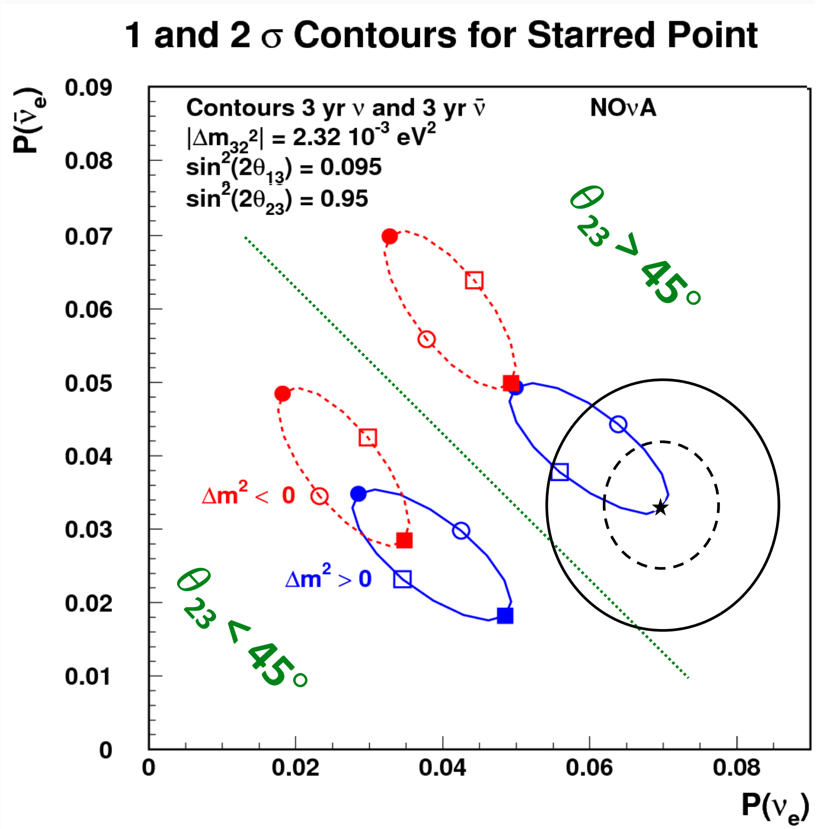
- If $\sin^2 2\theta_{23}$ is not maximal there is an ambiguity as to whether θ_{23} is larger or smaller than 45°
- The $\sin^2\theta_{23}$ is unimportant when comparing accelerator experiments; however, it is crucial in comparing accelerator to reactor experiments
- The $\sin^2 2\theta_{23}$ is measured via $\nu_\mu \rightarrow \nu_\mu$

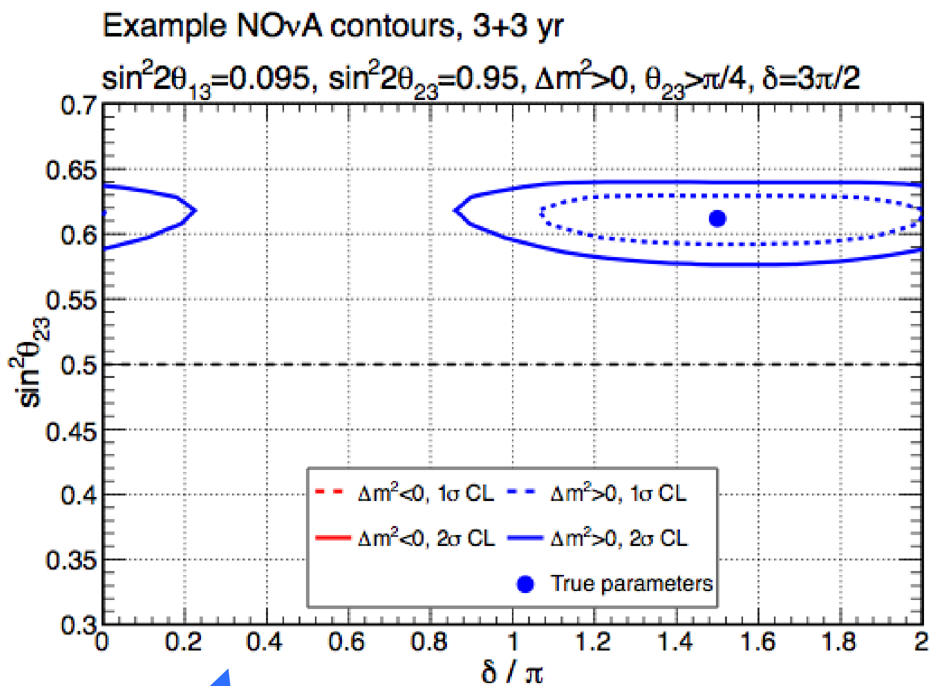
$$P(\nu_e) \propto \sin^2(\theta_{23})\sin^2(2\theta_{13})$$

$\Rightarrow$ ***θ_{23} octant sensitivity***

Non-maximal $\sin^2 2\theta_{23}$ and NOvA

- Expected contours for one example scenario using 3 years of data for each neutrino mode
- Assuming tight measurement of θ_{13} from reactors





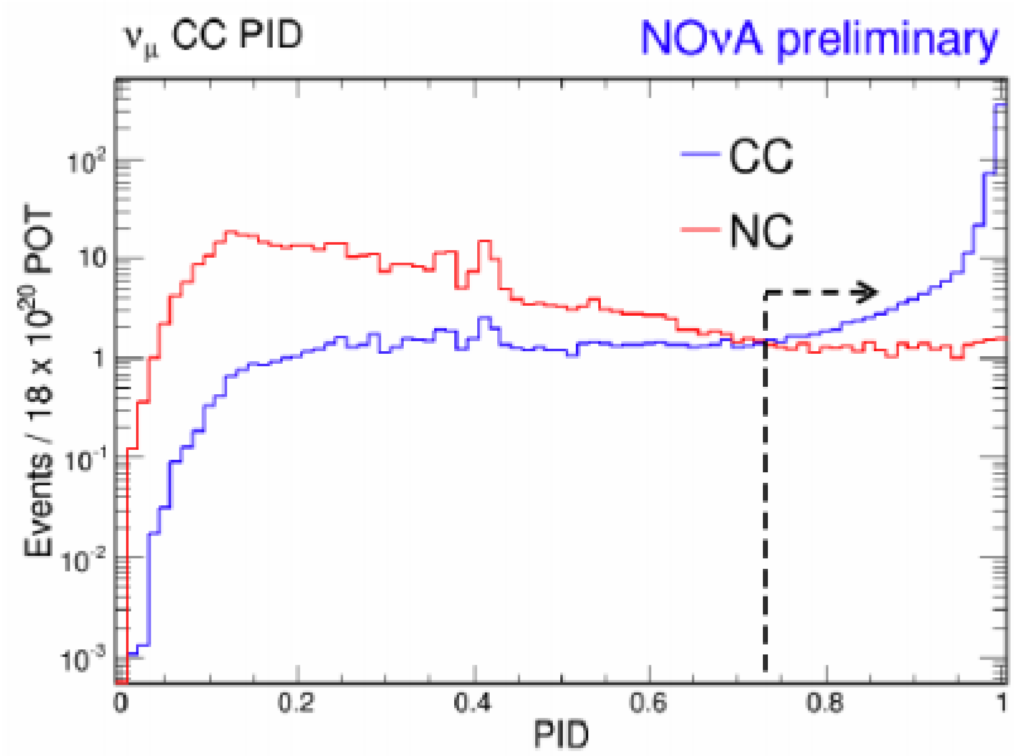
Simultaneous hierarchy, CP phase, and θ_{23} octant information from NOvA

- Combine with NOvA ν_μ analysis for θ_{23} constraints
- In this favourable case we distinguish hierarchy and octant at > 2σ
- Rule out half of δ_{CP} space (2σ)

$\nu_\mu \rightarrow \nu_\mu$ Disappearance

Selecting muon neutrinos

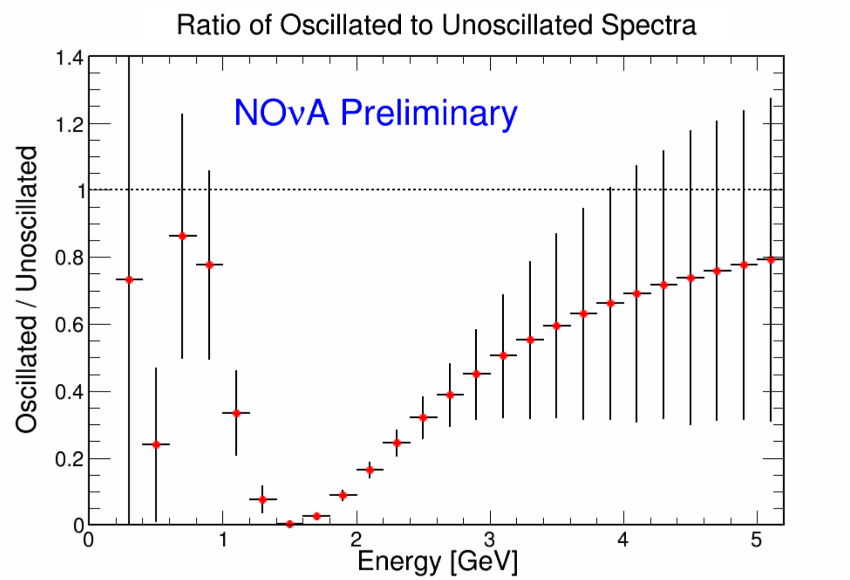
- Muon tracks are identified using a multi-variate analysis based on reconstructed dE/dx, track length and scattering
- Separates NC events from ν_μ CC sample



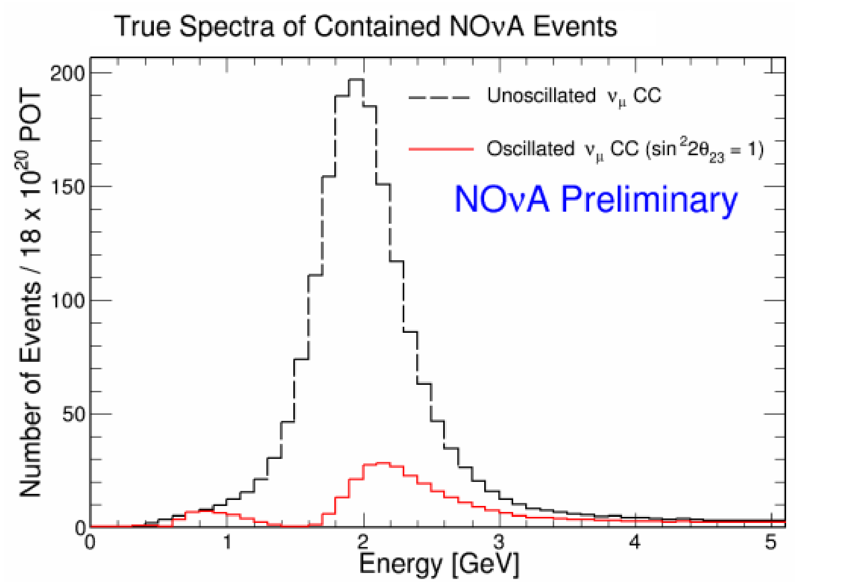
Sensitivity to $\sin^2(2\theta_{23})$

- Separate measurement of $\nu_\mu \rightarrow \nu_\mu$ gives access to $\sin^2(2\theta_{23})$ and $|\Delta m^2_{32}|$
- Basic disappearance probability:

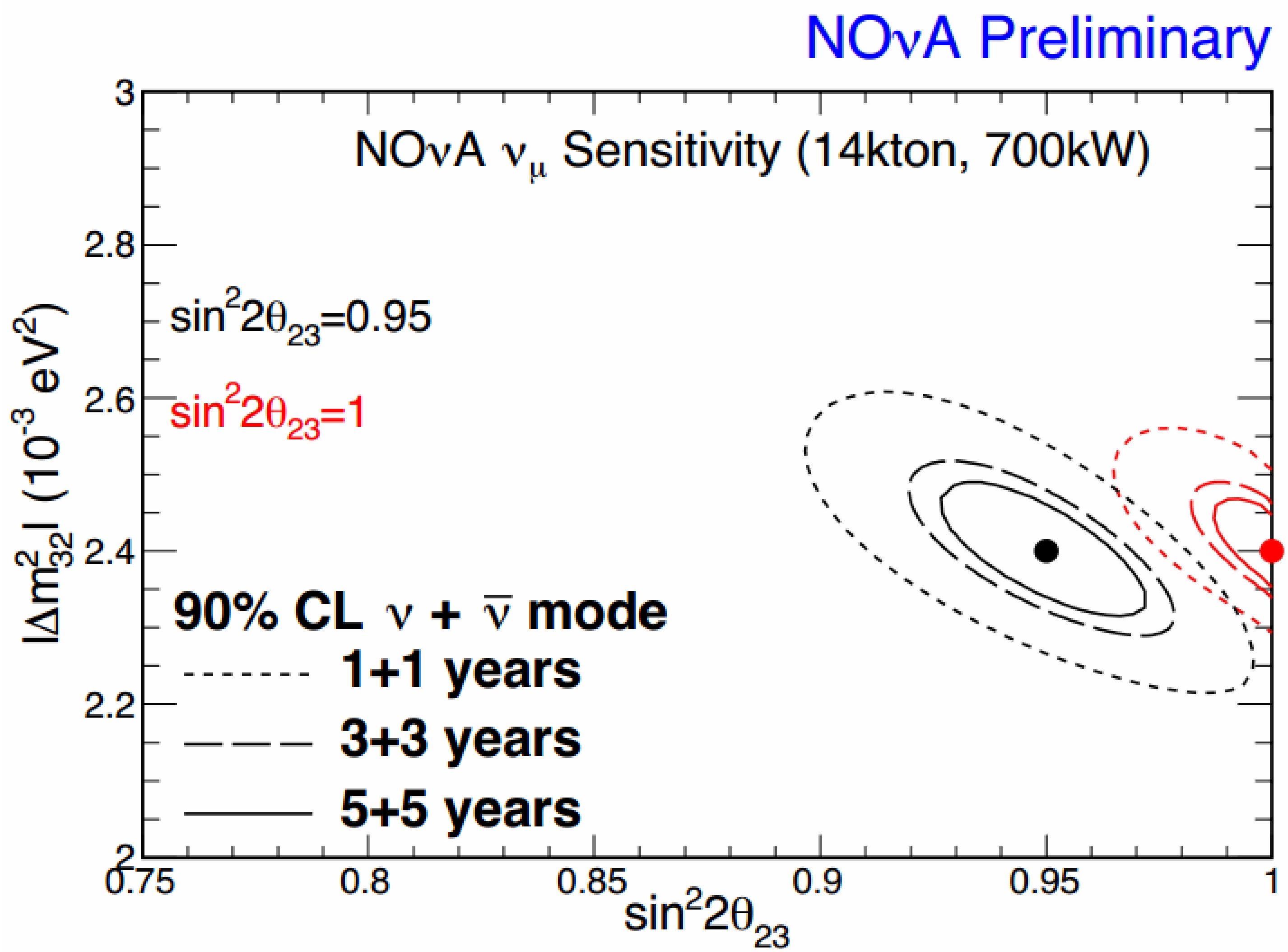
$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\Theta_{23})\sin^2\left(\frac{1.27\Delta m_{32}{}^2 L}{E}\right)$$



- With a baseline of L = 810 km and neutrino energy spectrum peaked at E = 2 GeV, NOvA is optimal for ν_μ disappearance



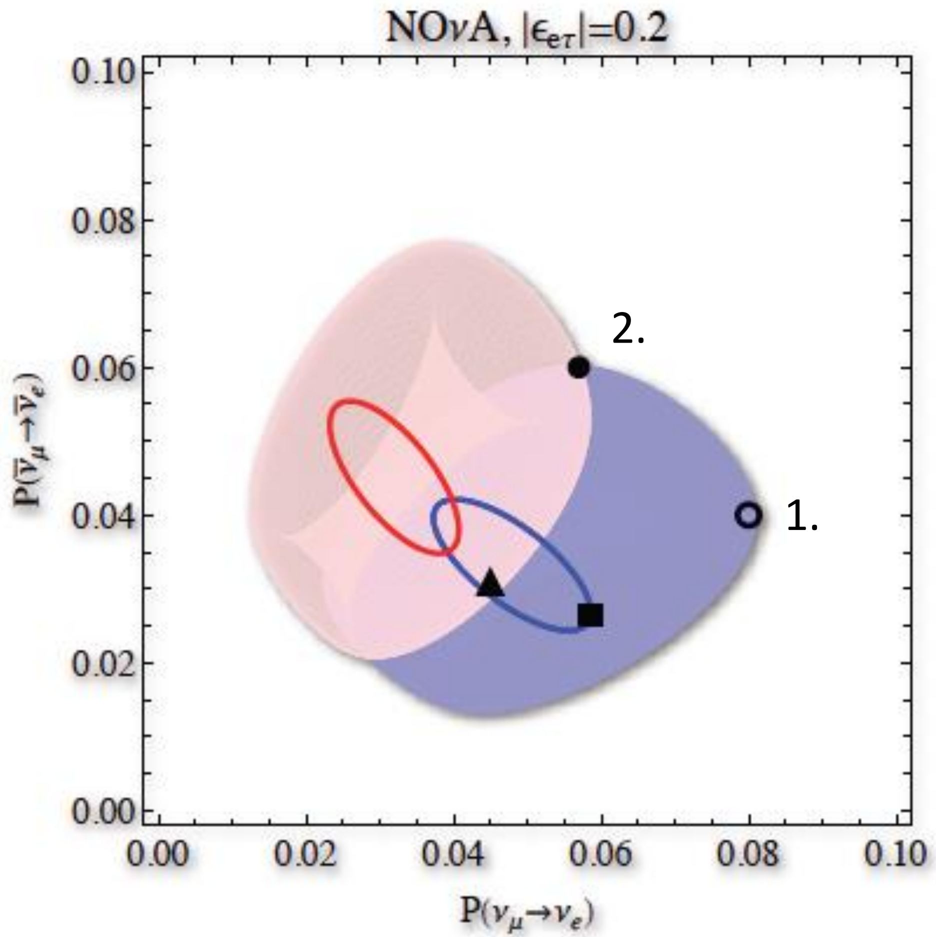
Full Reach of ν_μ Sensitivity



- If $\sin^2 2\theta_{23}$ = 0.95, able to exclude (at the 90% CL) maximal θ_{23} after 1+1 years

Non-Standard neutrino Interactions (NSI)

- NOvA bi-probability plots assume standard neutrino interactions
- Allowing for non-zero NSI in the e-τ sector, $|\epsilon_{e\tau}|$=0.2, expands the hierarchy regions significantly
- Consider qualitative possibilities:
  1. NSI and hierarchy determination
  2. NSI determination only



A. Friedland & I. Shoemaker
arXiv:1207.6642v1 [hep-ph]

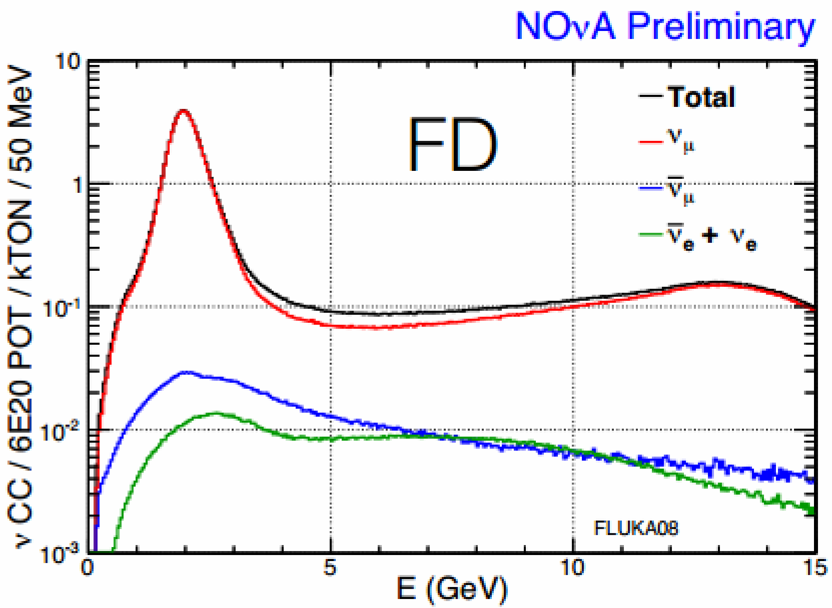
Summary

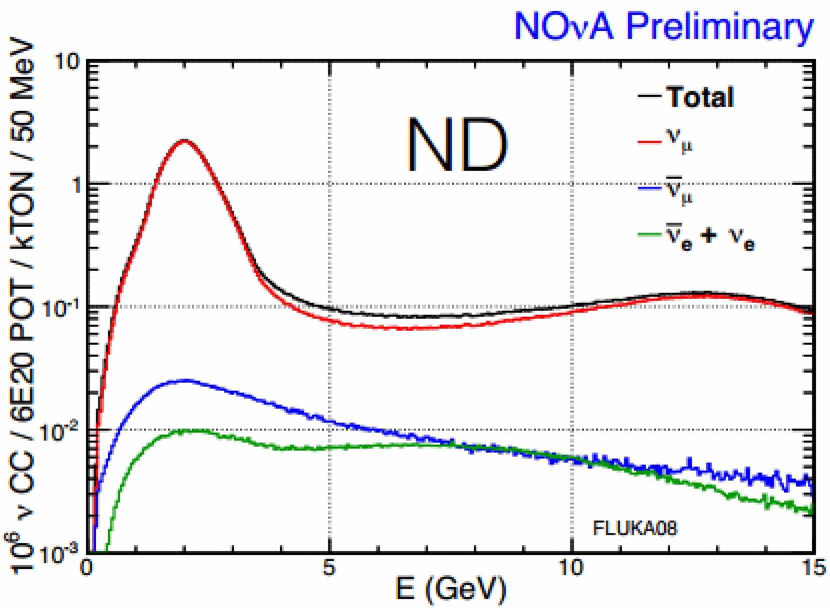
- NOvA will make many important contributions to neutrino physics:
  - Measurement of θ_{13}
  - Important first information on the neutrino mass hierarchy and CP violating phase
  - Determination of the θ_{23} octant
  - More precise measurements of $|\Delta m^2_{32}|$ and $\sin^2(2\theta_{23})$
- First far detector blocks have been installed and now collecting cosmic ray data
- Near detector muon catcher installed, first half of detector will be completed by end of this calendar year
- NuMI beam expected to return within the next few weeks
- Collaboration is very focused on commissioning of Far Detector
- Reconstruction/analysis tools are in place for first results in summer of 2014

Thank you to the organisers and Los Alamos National Laboratory for the invitation to speak on behalf of the NOvA collaboration!

Backup

Neutrino Beam Mode





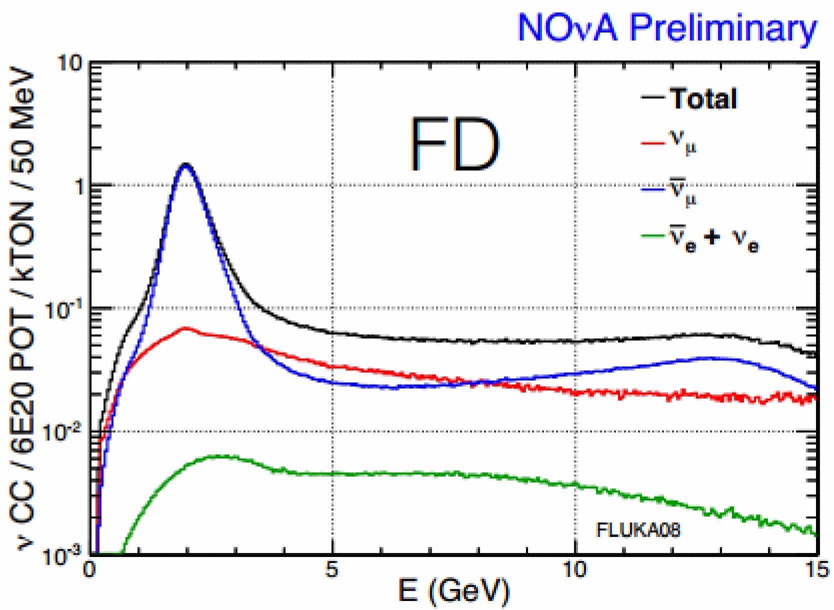
	[1,3]GeV	[0,120]Gev
Total	63.5	103.8
Numu	62.1	97.6
Anti-Numu	1.0	3.9
Nue+Anti-Nue	0.4	2.3

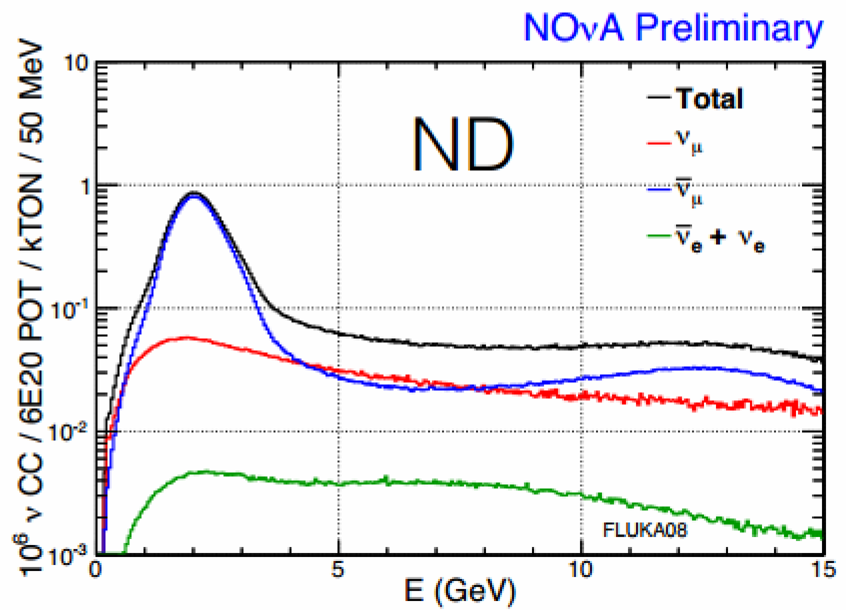
x10[6]	[1,3]GeV	[0,120]Gev
Total	53.9	95.0
Numu	52.6	89.5
Anti-Numu	0.9	3.5
Nue+Anti-Nue	0.4	2.0

[1,3]GeV: $(\nu_e + \bar{\nu}_e)/\nu_\mu = 0.6\%$

[1,3]GeV: $(\nu_e + \bar{\nu}_e)/\nu_\mu = 0.7\%$

Anti-neutrino Mode





	[1,3]GeV	[0,120]Gev
Total	25.1	46.7
Numu	2.4	13.2
Anti-Numu	22.5	32.2
Nue+Anti-Nue	0.2	1.3

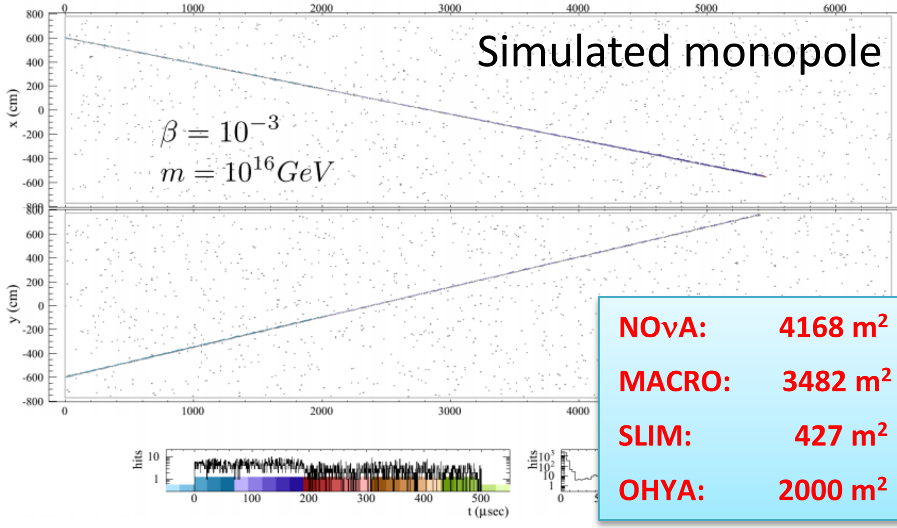
x10⁶	[1,3]GeV	[0,120]Gev
Total	21.4	42.3
Numu	2.1	11.9
Anti-Numu	19.1	29.3
Nue+Anti-Nue	0.2	1.1

[1,3]GeV: $(\nu_e + \bar{\nu}_e)/\nu_\mu = 0.8\%$

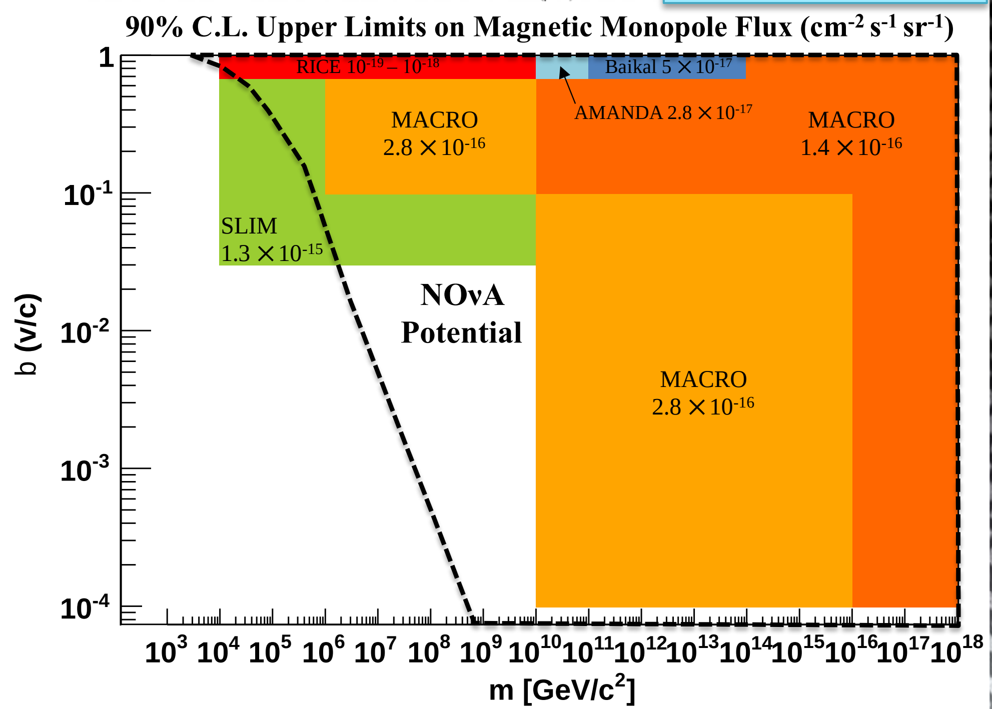
[1,3]GeV: $(\nu_e + \bar{\nu}_e)/\nu_\mu = 1.0\%$

Exotic Searches

- Because the NOvA detector is so large and highly-segmented, it lends itself to exotic searches:
- Magnetic Monopoles
  - would be highly ionizing or slow moving particles
  - The NOvA detector is favorable because of its large surface area and its surface location
  - The plot on the right shows the monopole phase space we have access to
- Supernovae
  - have a large neutrino shockwave
- WIMP
  - highly energetic neutrinos coming from the sun
- Sterile Neutrinos & NSI
- Using the Near Detector:
  - Neutrino Magnetic Moment
  - Dark Sector

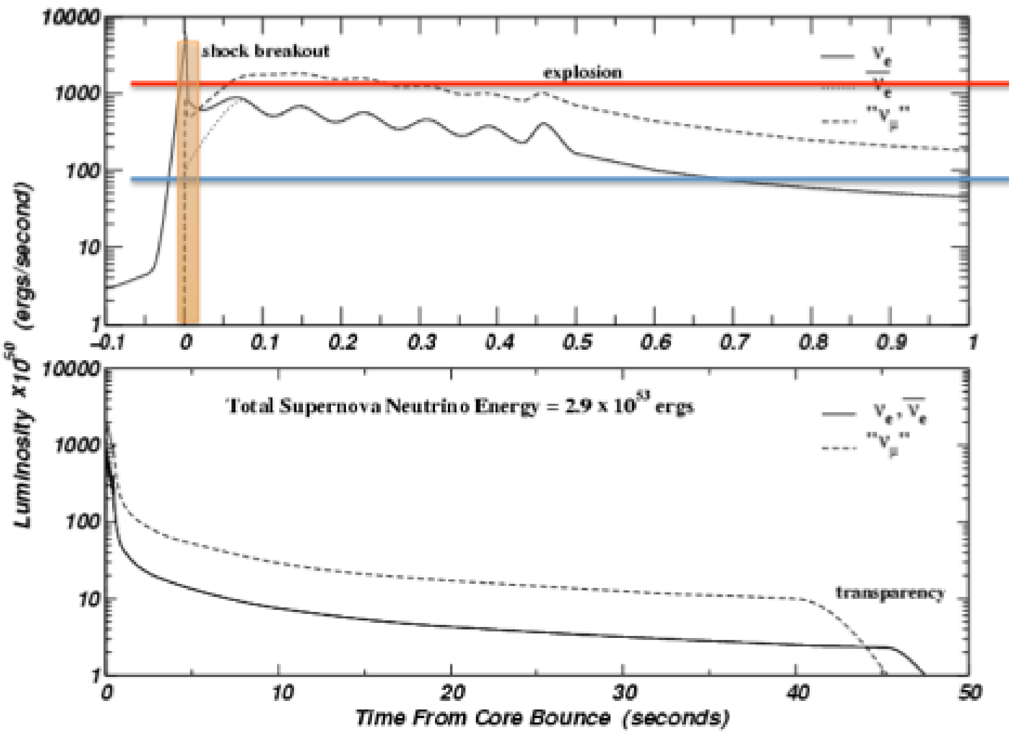


NOvA:	4168 m^2
MACRO:	3482 m^2
SLIM:	427 m^2
OHYA:	2000 m^2



Supernova Neutrinos

- NOvA is not underground, however it is a segmented detector with a very flexible data-driven trigger

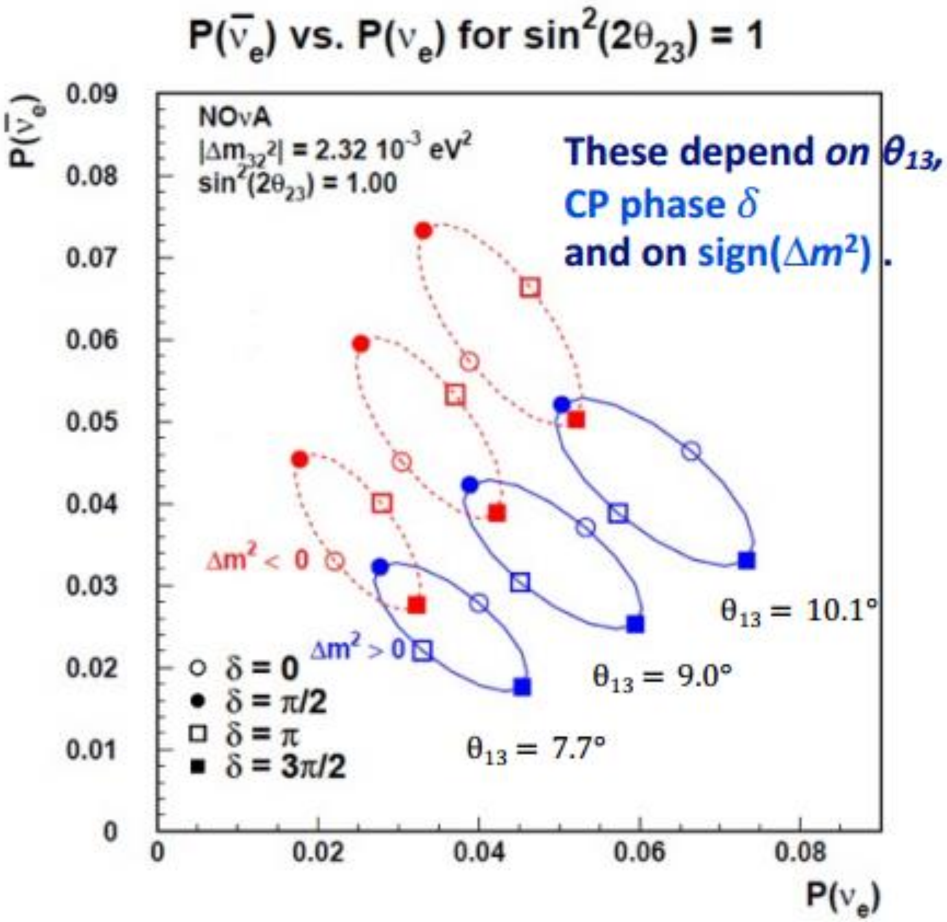


- We will see ~4k neutrinos for a supernova burst in our galaxy
- NOvA has continuous digitisation which allows us to look for unusual 2-3 plane coincidence rates
- Within the first 10 ms it will raise abour a peak threshold, signaling to record these and future data

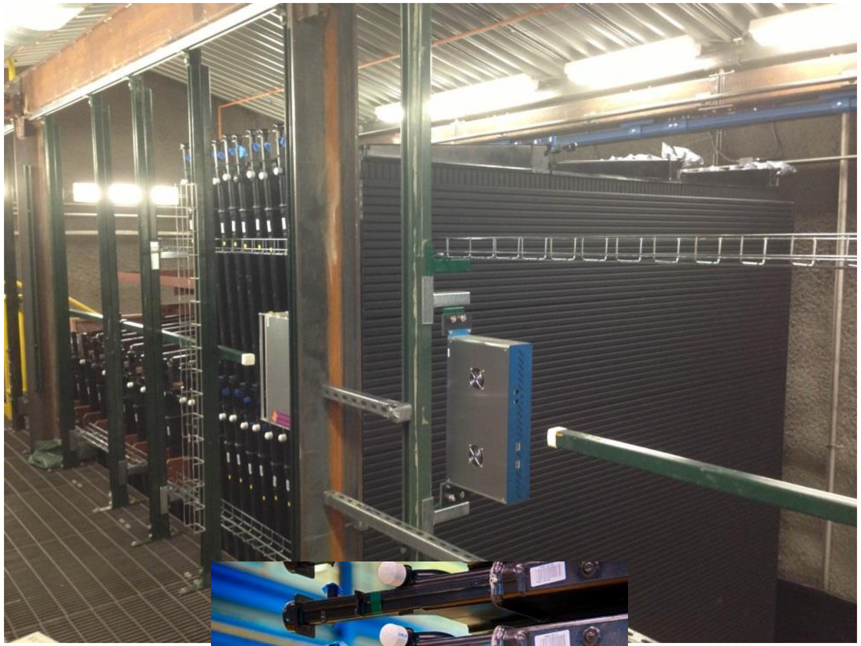
- NOvA can provide information on the time profile and energy of SN neutrinos

NOvA measurements

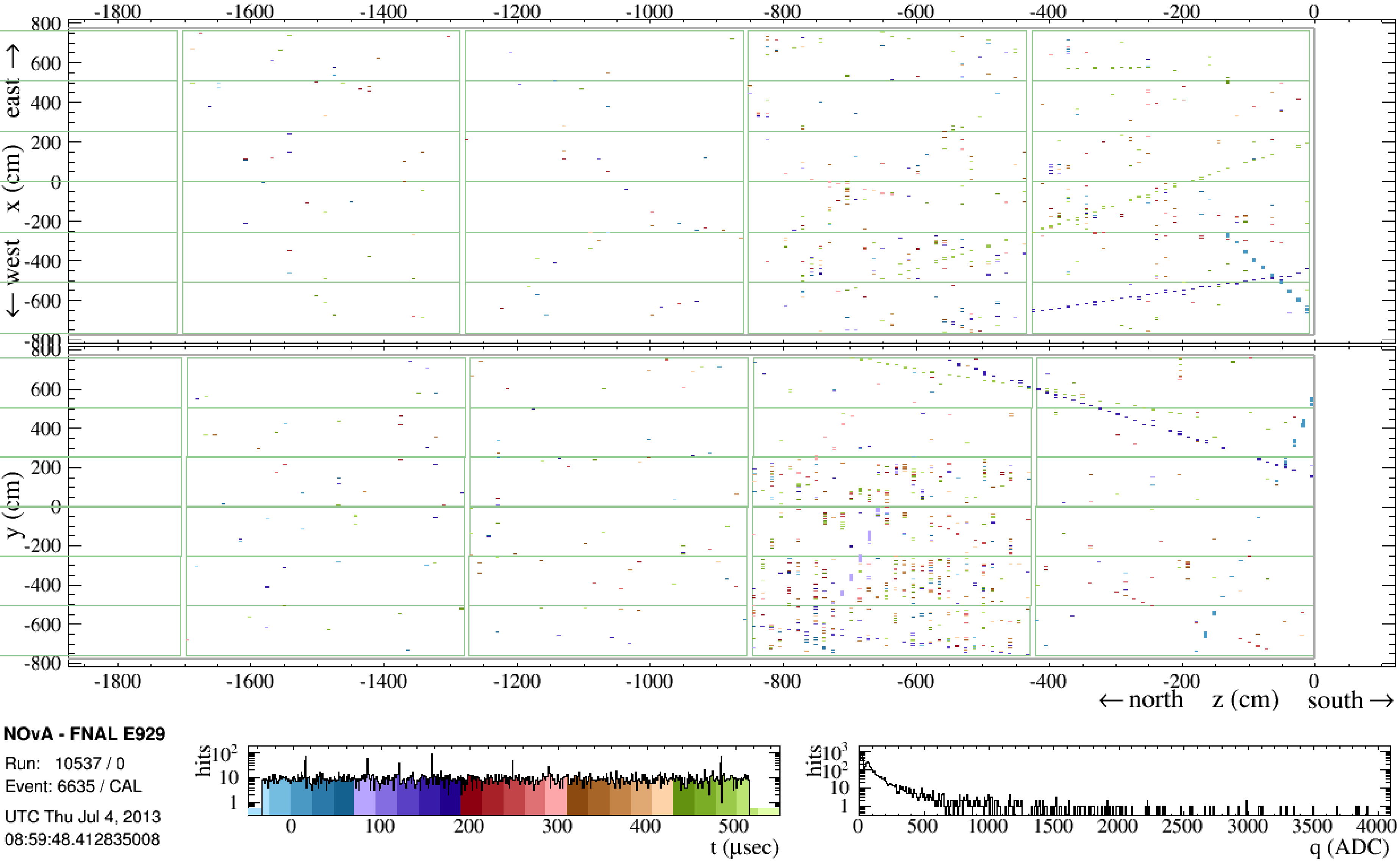
- NOvA will measure: $P(\nu_\mu \rightarrow \nu_e)$ at 2 GeV and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ at 2 GeV



Near Detector installation



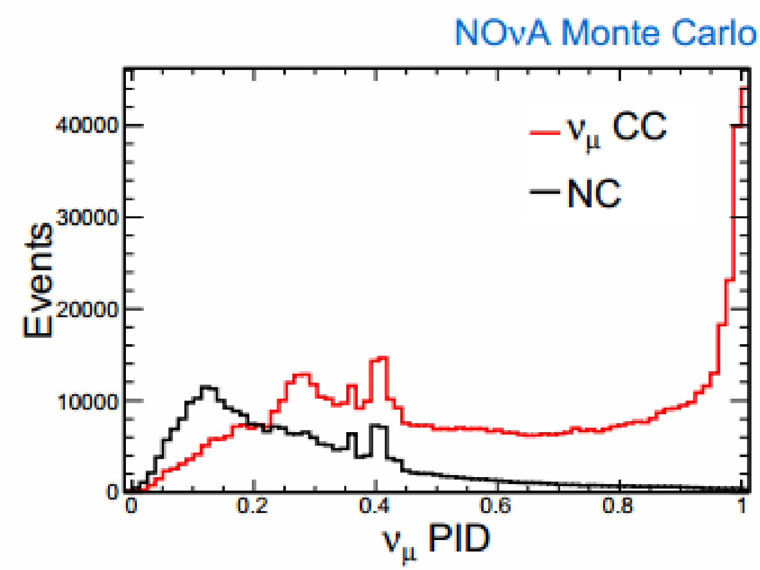
Far Detector Cosmic Ray Event Display (Two Di-blocks)



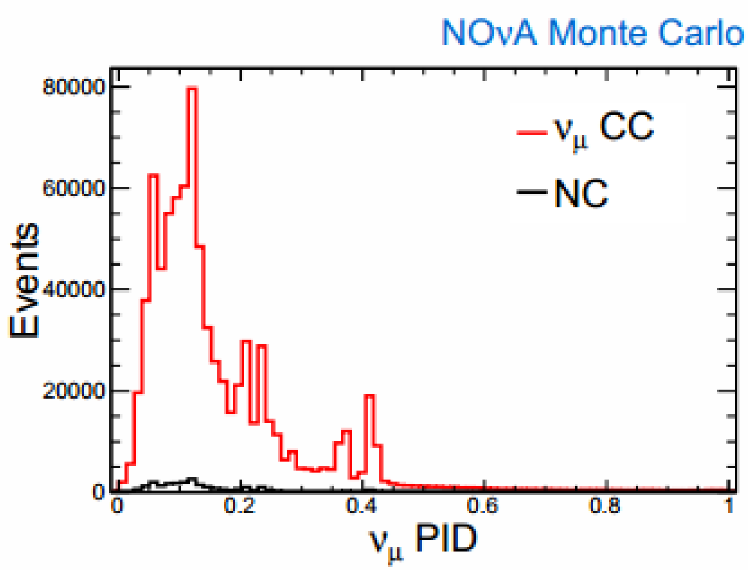
Near Detector On Surface (NDOS)

- Designed to prototype all detector systems prior to any installation at Ash River as a full end-to-end test of systems integration and installation
- Gained experience in qualifying oil and testing our oil filling procedures in advance
- Tested APDs in realistic operating conditions
- NDOS has 64 cells x 100 planes (X) + 96 cells x 99 planes (Y)
  - Far Detector has 384 cells x 960 planes
- Installation completed May 9^{th} 2011
- Commissioning and neutrino data collection 11/2010 – April 30^{th} 2012

- ν_μ PID shows that after muon removal, events do not look ν_μ CC like



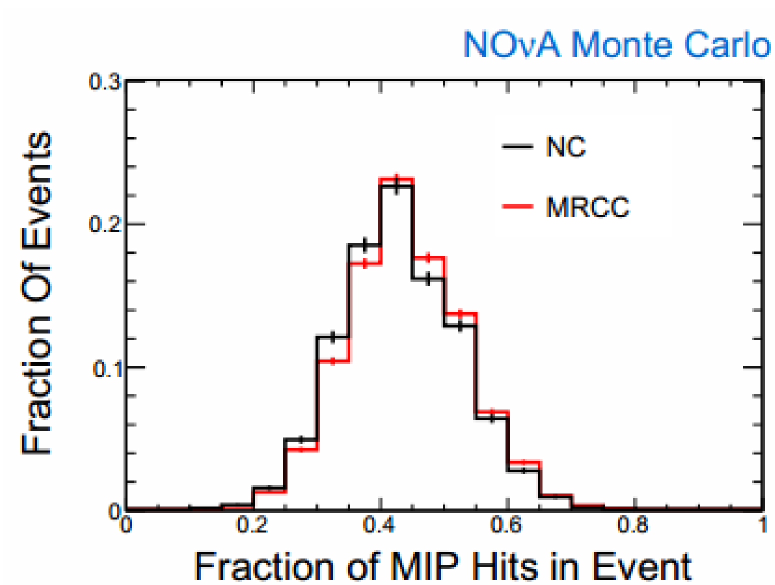
ν_μ PID before muon removal

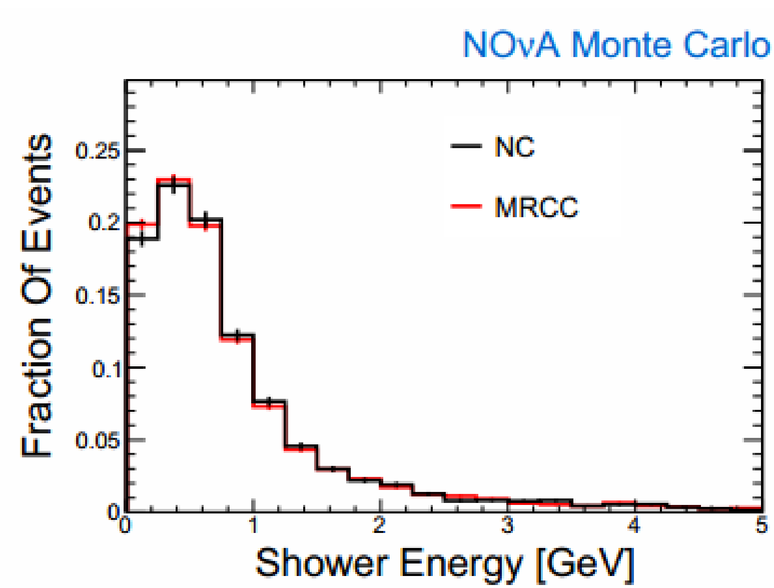


ν_μ PID after muon removal

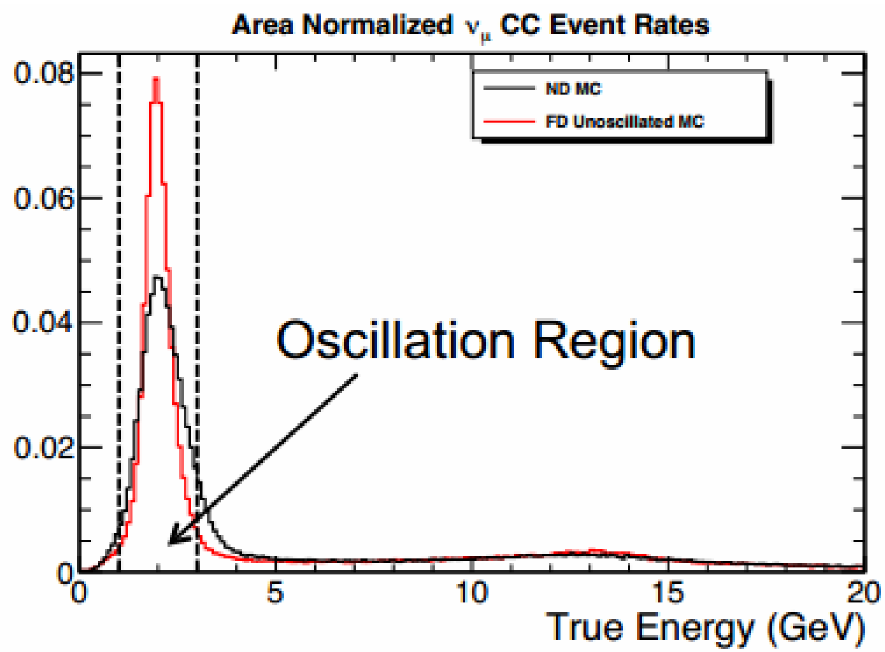
MRCC Similarity to Neutral Current Events

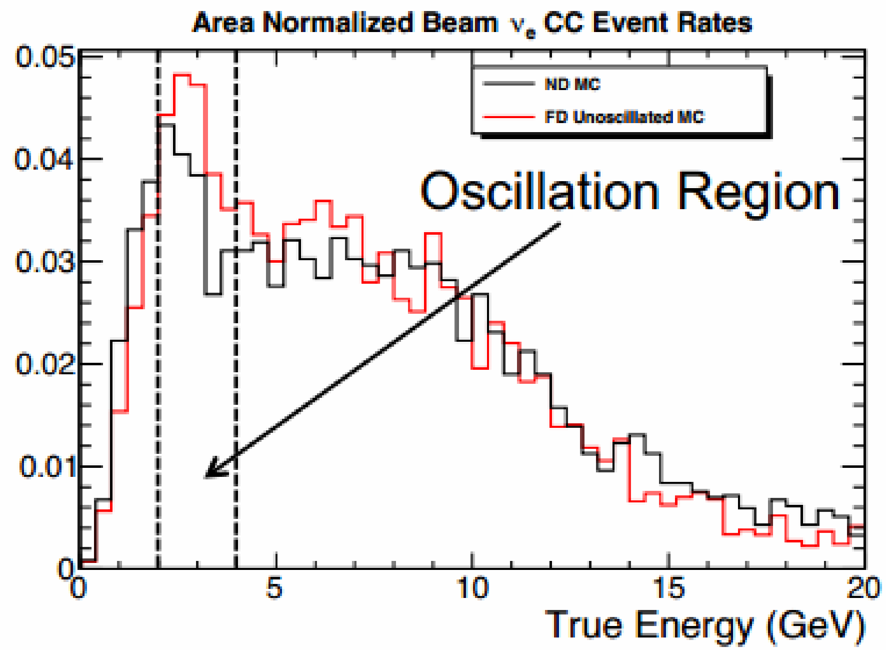
- Several checks have been performed to test the likeness of MRCC events to Neutral Current (NC) events
- MRCC and NC samples look similar in low as well as high level variables





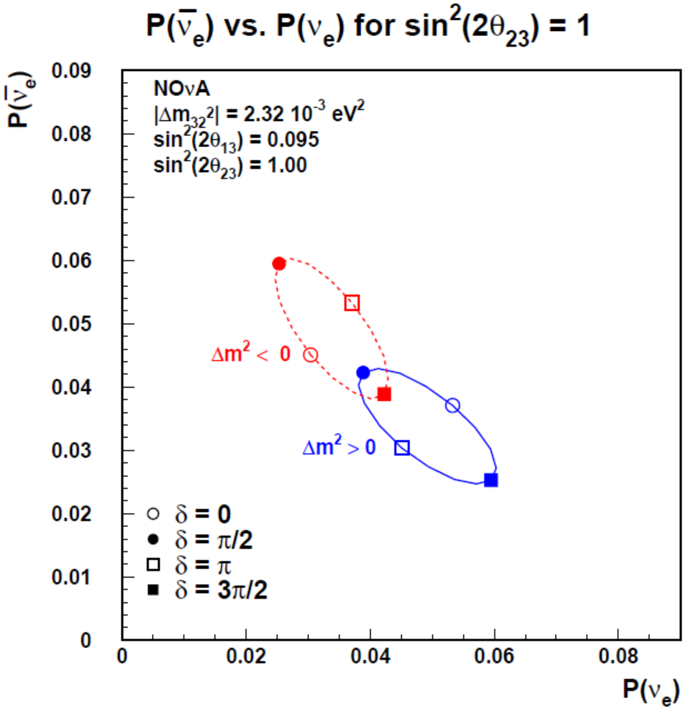
Predicting the Far Detector background





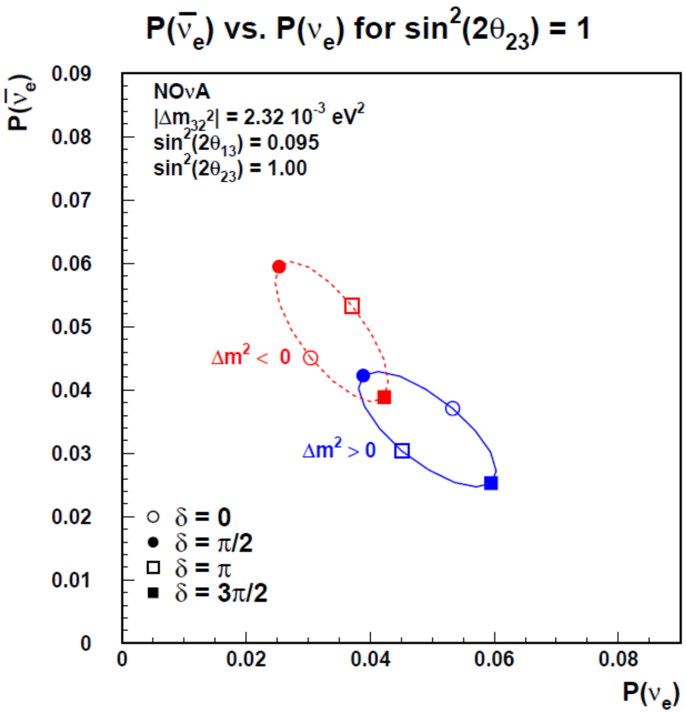
- Area normalized event rates demonstrate differences in detector spectra shapes. A F/N ratio can be made from the non-normalized versions
- These spectra are the true events with no selections applied. The F/N ratios change when various selections or PIDs are applied

Non-maximal $\sin^2 2\theta_{23}$



- If $\sin^2 2\theta_{23}$ is not maximal there is an ambiguity as to whether θ_{23} is larger or smaller than 45°
- The $\sin^2\theta_{23}$ is unimportant when comparing accelerator experiments; however, it is crucial in comparing accelerator to reactor experiments
- The $\sin^2 2\theta_{23}$ is measured via ν_μ disapperance

Non-maximal $\sin^2 2\theta_{23}$



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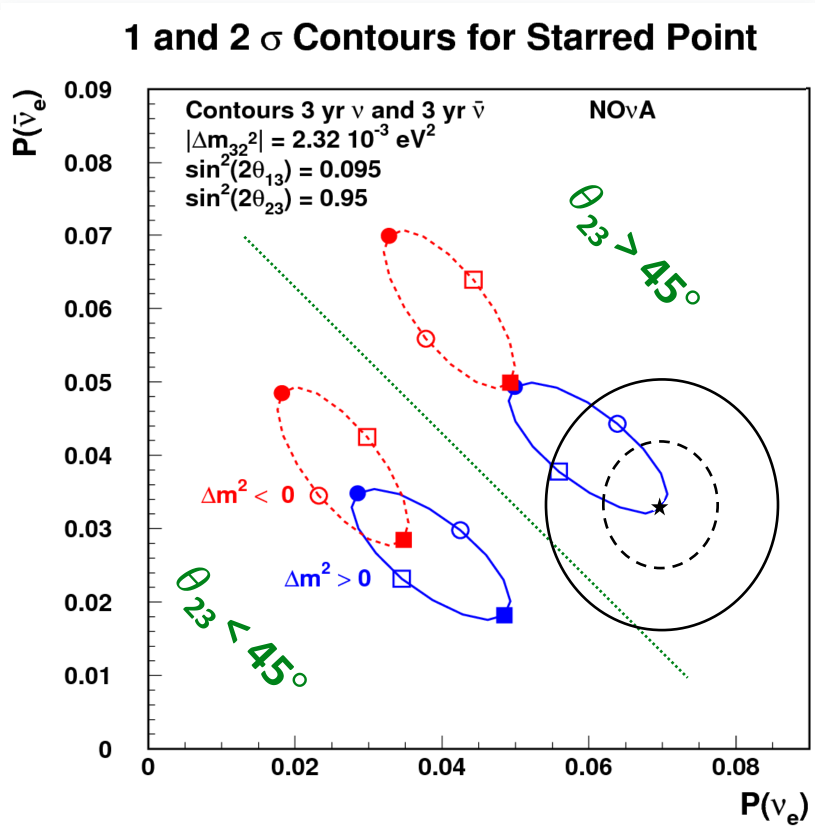
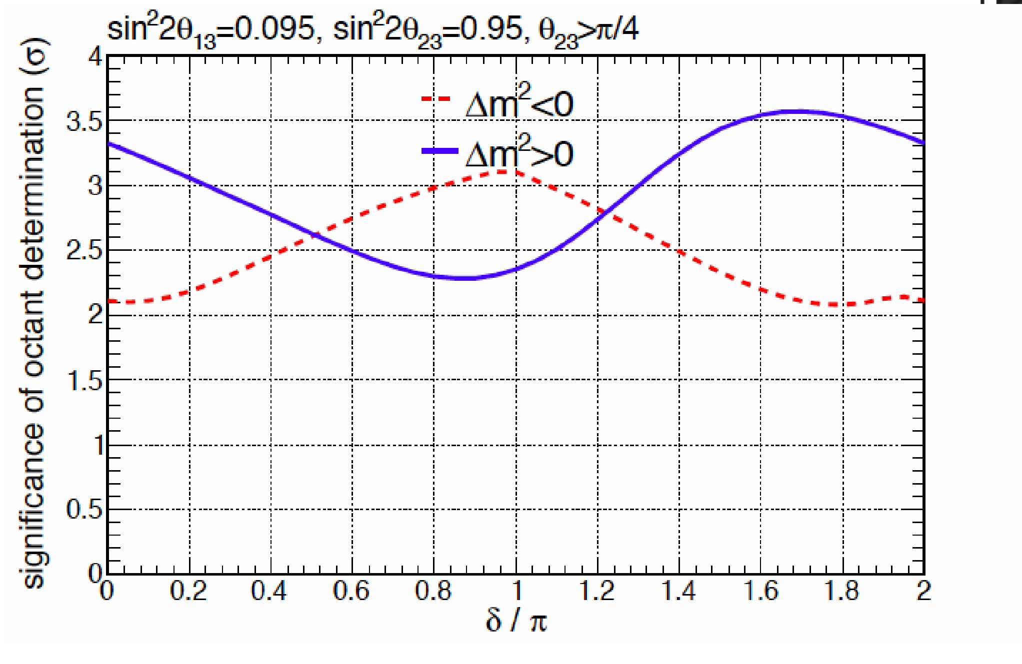
$$P(\nu_e) \propto \sin^2(\theta_{23})\sin^2(2\theta_{13})$$

⇨ ***θ_{23} octant sensitivity***

Non-maximal $\sin^2 2\theta_{23}$ and NOvA

- Expected contours for one example scenario using 3 years of data for each neutrino mode
- Assuming tight measurement of θ_{13} from reactors





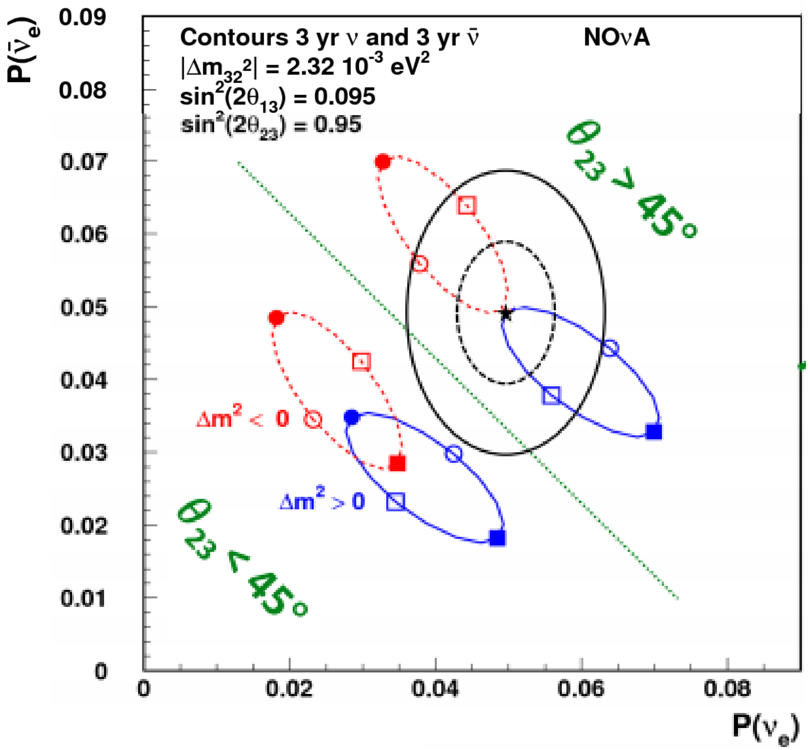
Simultaneous hierarchy, CP phase, and θ_{23} octant information from NOvA

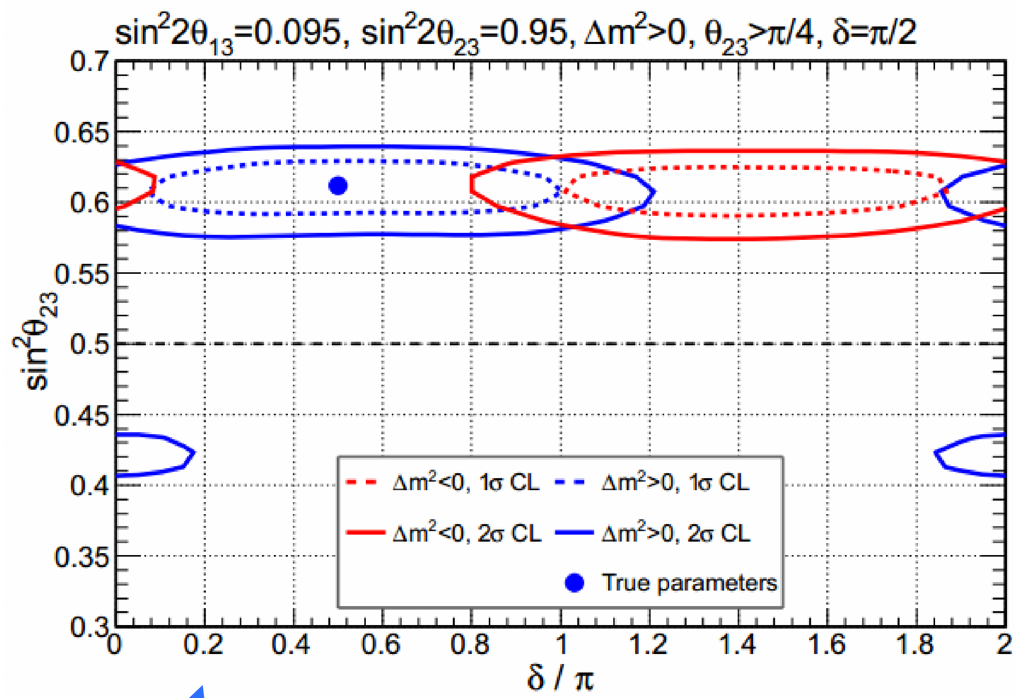
- Octant sensitivity less dependent on δ and hierarchy
- In this case ($\sin^2 2\theta_{23} = 0.95$, $\theta_{23} > \pi/4$) determine octant at better than 2σ for any δ and hierarchy

Non-maximal $\sin^2 2\theta_{23}$ and NOvA

- Expected contours for one example scenario using 3 years of data for each neutrino mode
- Assuming tight measurement of θ_{13} from reactors

1 and 2 σ Contours for Starred Point

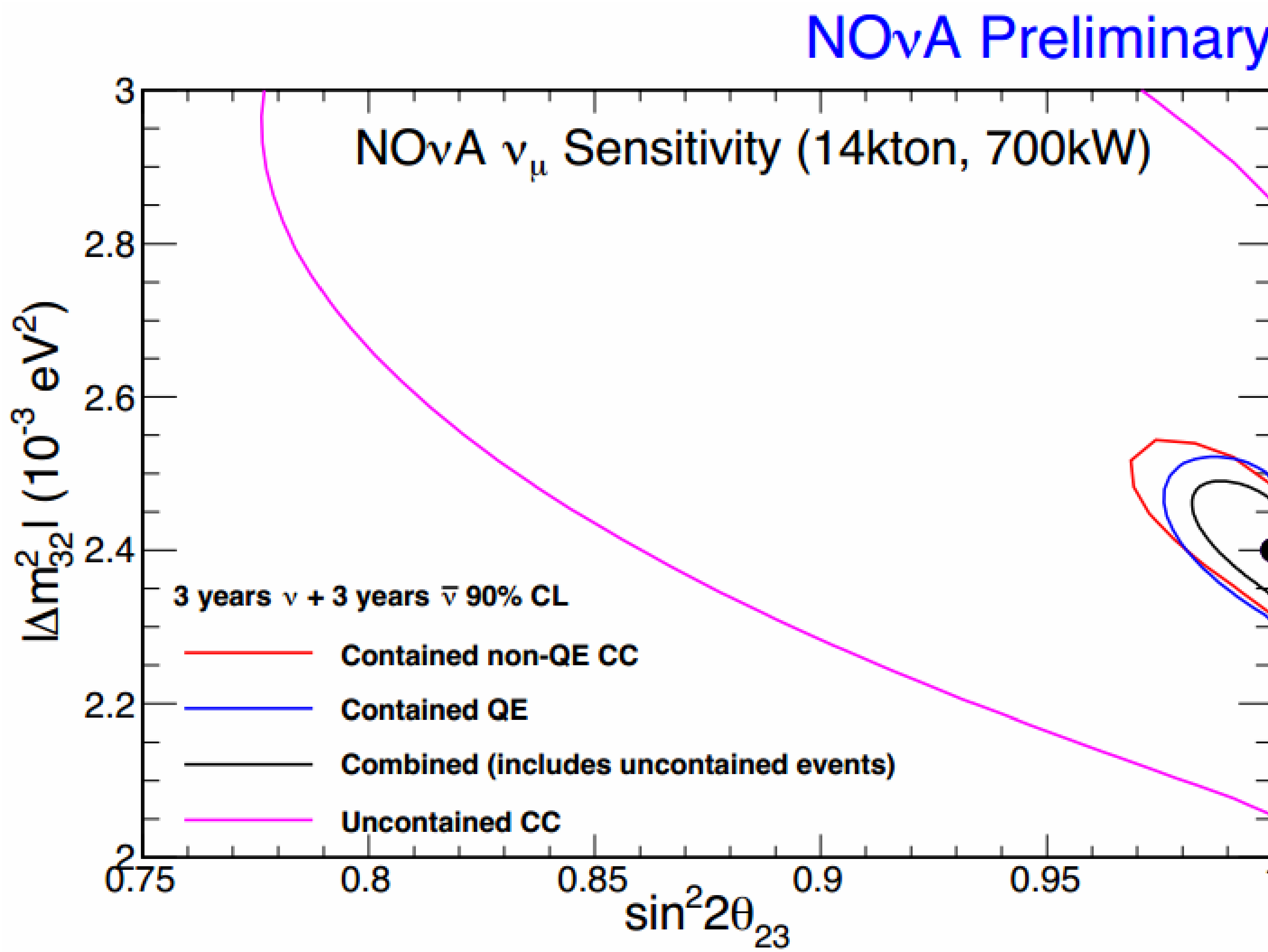




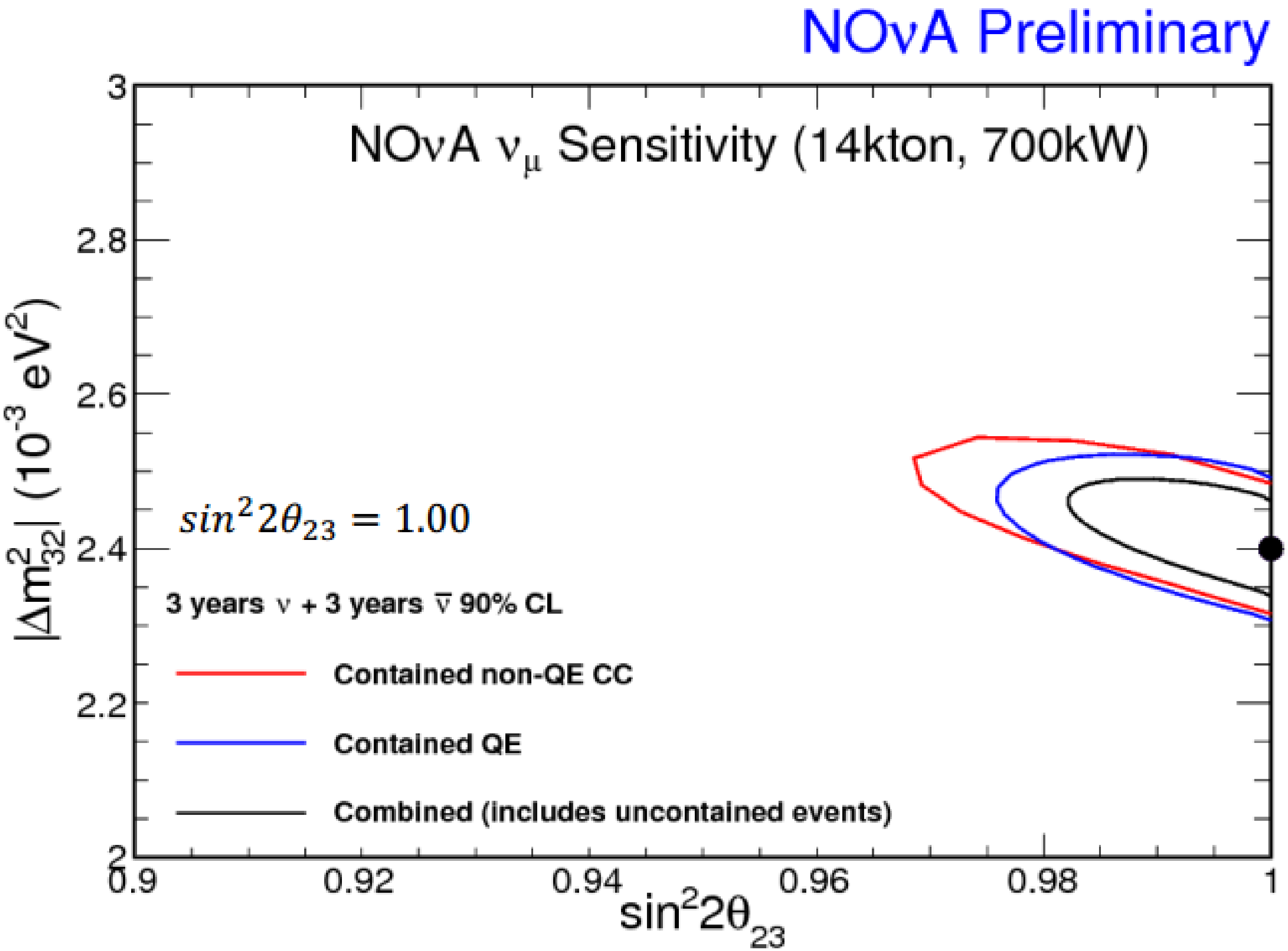
In "degenerate" cases, hierarchy and δ information is coupled. θ_{23} octant information is not

- Octant information mostly independent
- In this case ($\sin^2 2\theta_{23} = 0.95$, $\theta_{23} > \pi/4$) determine octant at better than 2σ for almost any δ and hierarchy

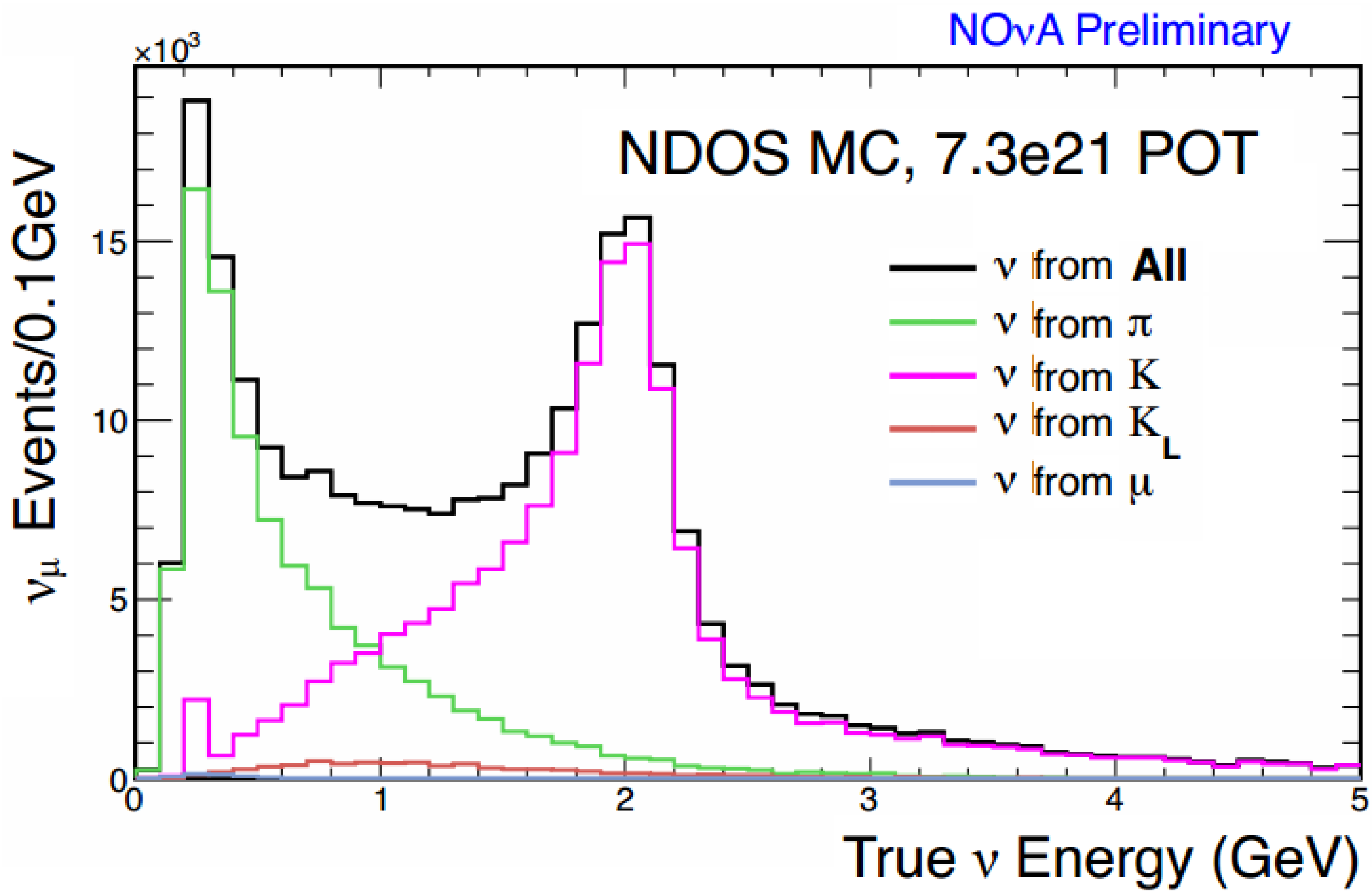
Combined ν_μ Sensitivity



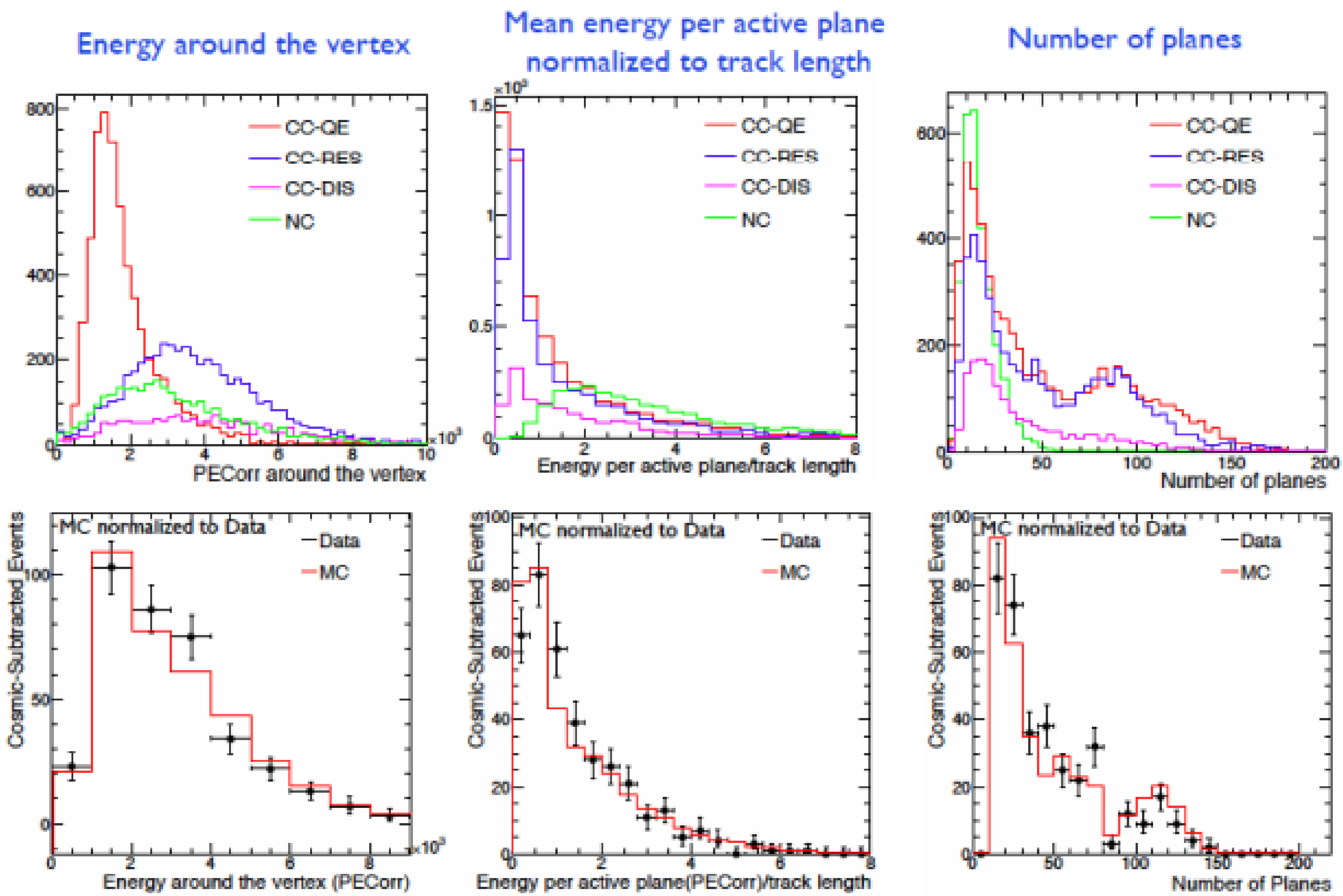
Combined ν_μ Sensitivity



NuMI Beam Spectrum in NDOS



Measurement of ν_μ CC QE Cross-Section in NDOS (M. Betancourt, first NOvA PhD Thesis)



- Multivariate analysis based on reconstructed quantities used to separate QE from non-QE and NC events
- Shapes of MC distributions agree well with data